An Investigation into the Design of an Unmanned Ship

By

Paulo Eduardo Meirelles Freire

A thesis submitted for the M.Phil. Degree in Mechanical Engineering

upervisors:

r. Richard W. G. Bucknall

'of. John van Griethuysen

Department of Mechanical Engineering

University College London

July 2002

ACADEMIC REGISTRAR
ROOM 261
UNIVERSITY OF LONDON
SENATE HOUSE
MALET STREET
LONDON WC1E 7HU

MEMORANDUM

The accompanying thesis covers the research work carried out by the author at University College London between September 2000 and July 2002 and is duly submitted for consideration for the award of M.Phil.

The investigations centre on the design of an unmanned ship as a possible answer to the maritime manpower shortage forecasted for the coming years, proposing solutions for foreseen technological challenges and comparing the profitability of the concept against a state-of-the-art merchant vessel.

It is the author's belief that all the investigations, ideas and work in this thesis are original unless otherwise acknowledged in the text by reference.

The author claims to have made the following contributions to the subject of naval architecture and marine engineering:

1. A complete evaluation of the impact of maintaining a crew on board a merchant ship was undertaken, resulting in a novel economic analysis of the balance between manning and automation levels for the maritime industry.

2. The design of a navigation system capable of taking a vessel from berth to berth without the need of human interference was presented.

3. The design of an unmanned propulsion plant was developed in order to achieve a failure rate better than those expected to be observed on a conventionally manned vessel currently in operation at sea.

4. Alternative measures were proposed to cope with the absence of people on board to perform tasks in the areas of communications, safety and security.

5. A complete unmanned ship design was developed in a way that direct comparisons can be made between the proposed concept and a conventional state-of-the-art vessel, both in terms of technical issues and in terms of profitability

Date: 30/07/2002

ABSTRACT

An Investigation into the Design of an Unmanned Ship

The shipping industry is again facing a shortage of manpower, a situation similar to the one experienced in the 1960's, which caused the first wave of widespread introduction of automation on board merchant ships, thereby enabling substantial crew reductions throughout the world fleet.

The automation process has continued at an increasing pace with the introduction of 'periodically unattended machinery spaces' and 'integrated bridge control systems', which have made "one man on watch" operations possible aboard many merchant ships.

However, information overload being experienced by seafarers on highly automated ships, together with the life style due to working watches, limited onboard companionship and very short periods ashore, are seen as sources of stress, fatigue and psychological strain, which can compromise the effectiveness of a crew and consequently the safety of the vessel.

Further slimming of crews is therefore highly unlikely, despite the continuing high costs of manpower, and a new concept in ship design and operation will be needed, if the present manpower problems and further cost reductions are to be addressed.

The project aims were to investigate, from technical and economic viewpoints, the feasibility of a totally automated, unmanned ship as an option to solve the existing manpower difficulties at sea.

An analysis of the marine manpower forecast as well as the calculation of the true total cost of a crew in ship procurement and operation is presented. An engineering assessment has been undertaken in key automated systems and their operation philosophies needed in a ship designed to eliminate the crew in the key areas of navigation, propulsion and damage control.

Finally, a complete ship design is presented and the cost, profitability and safety of this new concept will be compared with those achieved by state-of-the-art conventional designs.

TABLE OF CONTENTS

LIST OF FIGURES

Figure N°

Figure N°

Figure N°

Figure N°

LIST OF TABLES

Table N°

LIST OF ANNEXES

Annex N°

NOMENCLATURE

In order of appearance in text.

drms : Distance root mean square - the radius of a circle that contains at least 95 percent of all possible fixes that can be obtained with a system at any one place.

MTTF : Mean Time to Failure

MTBF : Mean Time Between Failures

R(t) : Exponential Reliability Time Distribution = $e^{-\lambda t}$

λ : Failure rate

TEU : Twenty Foot Equivalent Unit (20' x 8' x 8'6")

Vs : Superstructure Proportion = $\frac{\text{Sup. Volume}}{\text{Sup. Volume} + \text{Main Hull Volume}}$

L : Length

B : Beam

D : Depth

T : Draught

V : Total Enclosed Volume

K_B : B/T

Δ : Displacement

∇ : Underwater Volume

Ⓜ : Circular M = $\frac{L}{\nabla^{1/3}}$

C_B : Block Coefficient

C_M : Midships Coefficient

C_P : Prismatic Coefficient

$P_{S(mcr)}$: Shaft Power, Maximum Continuous Rating

CHAPTER 1

INTRODUCTION

1.1 Motivation

Since the early 1990s, the potential shortage of qualified and competent officers has been a constant concern to the maritime industry.

For reasons related to the global economical and political changes, predictions of a severe manpower shortage have not yet come to pass, although some companies are currently facing difficulties when recruiting seafarers in particular grades [1].

After the publication of the ISF/BIMCO 2000 Manpower Update [1], it became clear that a small manpower deficit already exists with a strong tendency and likelihood for this to increase to become a very serious problem in the next decade.

The little general appeal that sea-going life now holds all over the world [2], allied to new competence standards demanded by the industry and regulated by the International Maritime Organisation, are some of the factors that will reduce the number of candidates available to fill the forecasted manpower shortage.

It is not the first time the shipping industry is facing such a threat, since the worldwide fleet expansion of the 1960s and early 1970s caused a similar crisis.

At that time, the shipping industry responded with a widespread introduction of automation on board ships, significantly reducing manning levels, an initiative backed by more flexible regulations from Flag States and international organisations.

Automation on board has increased with time, until reaching a stage where "one man on watch" concepts (although not accepted by a number of Port and Flag States) are already routinely applied on board a number of vessels.

The main factor limiting further crew reductions by increasing automation on board appears to have shifted from technology to the ability of seafarers to cope with a working routine where limited onboard companionship, aggravated by life style due to working watches and very short periods ashore are commonplace.

It is because of these factors and in view of recent regulations (STCW 95, ILO, etc) and Union requirements (e.g. ITF), it is very unlikely that further reductions in manning levels will be possible or desirable.

In this context, the idea of a fully automated unmanned ship appears to provide a solution to the forecasted manpower problem and it is the objective of this thesis to perform a technical and economic assessment of such a concept.

1.2 Aims of the Investigation

In this thesis, a design of an unmanned ship is proposed and presented in a way that a direct comparison with a state-of-the-art conventional vessel is possible, as far as risks, limitations, safety and profitability are concerned.

In order to face the unavoidable scepticism of a conservative maritime industry, the investigation has concentrated on the use of well proven technology that is already commercially available or expected to be fully in service within the next six years and integrating them to make the concept of an unmanned ship possible.

Routine use of Unmanned Aerial Vehicles (UAV) and Autonomous Underwater Vehicles (AUV) in both military and civilian applications, broadband communication services and centimetre-level global positioning systems are examples of such technologies recently made available worldwide, which principles were applied in the novel design proposed in this thesis.

Once the aims of the project had been established, the following objectives of the investigation were identified:

- To identify the issues concerning the manpower shortage threat faced by the maritime industry;

- To determine the total cost of maintaining a qualified crew on board a merchant ship;

- To define the requirements for a totally automatic berth-to-berth navigation system for a vessel, identifying the risks and limitations involved in every phase and specifying and designing a suitable navigation system for an unmanned ship;

- To design an unmanned propulsion system with a probability of failure equal or lower than expected in a conventionally manned engine room currently in operation at sea;

- To identify labour-intensive safety and operational tasks such as fire fighting, towing and mooring and to propose suitable automated alternatives;

- To design a communication and data transfer system in order to enable the interaction between the unmanned ship and conventional vessels and to enable human interference from shore in case of emergency;

- To select a state-of-the-art vessel as a benchmark and to design an unmanned ship able to perform the same role;

- To compare the proposed unmanned ship with the benchmark in technical and economic terms;

- To draw conclusions and make recommendations as to the way ahead for the development of the unmanned ship concept.

1.3 Structure of the Thesis

In Chapters Two and Three, an analysis of the marine manpower forecast as well as the calculation of the true total cost of a crew in ship procurement and operation are presented as the main motivations behind the design of an unmanned ship.

Further on, in Chapters Four to Seven, an engineering assessment of the technical challenges presented by such a concept are undertaken and solutions are proposed for the main areas in which a operation of a ocean-going vessel can be divided, namely:

- Navigation in its wider sense, including activities such as route planning, position fixing, collision avoidance, weather routing and mooring procedures;
- Propulsion, with emphasis in designing an unmanned system as reliable as a conventionally manned propulsion plant;
- Communication and interaction with other vessels, port authorities, vessel traffic services, etc.

The design of the proposed automated systems always considered a minimum impact on the operation of other vessels and land-based components of the maritime transportation system as the main requirement.

After the discussion of the main technologies needed to be incorporated into the concept, a complete ship design is presented in Chapter Eight and compared against a conventional state-of-the-art vessel.

In Chapter Nine, an economical feasibility study is performed, culminating with a direct comparison between the required freight rate for both the conventional vessel selected as the benchmark and the proposed unmanned ship.

Finally, general conclusions and a final assessment of the unmanned ship concept are presented in Chapter Ten.

CHAPTER 2

MANPOWER FORECASTS

2.1 Introduction

In the early 1960's, in order to compete with the more cheaply manned and operated fleets of flags of convenience and the heavily subsidised Eastern block countries, shipping companies in Europe and Japan started to implement shipboard automation to reduce their operating costs, beginning a new era in the maritime industry.

The high cost of manpower was not, however, the only reason to invest in the substitution of seamen by automated processes. Throughout the worldwide fleet expansion of the 1960's and early 1970's, the shipping industry experienced a severe shortage of maritime manpower, which led flag states to be more flexible with regard to legislated manning scales and work practices [10].

Automation has since been continuously introduced on board ships up to the present day and it seems that with periodically unattended machinery spaces and "one man on watch" philosophies, this evolution is reaching its limits, not because of technology, but because of the human-machine interface.

Although the reasons are different from those in the 1960's, the marine industry is now experiencing similar manning issues and it seems that new concepts will have to be developed in order to cope with what could be a serious threat to the industry.

Since the early 1990s, the potential shortage of qualified and competent officers has been of constant concern to the maritime industry.

The first indications of such a shortage were publicised in 1990 by ISF[1] and BIMCO[2], with help from the Institute for Employment Research, Warwick University, and updated in 1995. For a number of reasons however, those predictions have not yet come to pass, mainly for the following reasons:

a) In the early 1990s there was evidence that recruitment levels increased significantly, when compared to those expected by the studies;

b) Political changes in Eastern Europe increased the number of seafarers readily available in the global market;

c) The number of ships in the world fleet increased at a slower rate than predicted by the studies;

d) The phasing out of the older ships that required higher manning levels;

e) Higher levels of automation, reducing crews to a minimum level.

Some problems nevertheless are already happening, such as the difficulties shipping companies face when recruiting seafarers in particular grades (e.g.. senior engineers) [1] and based on the recently published ISF/BIMCO 2000 Manpower Update [1], it becomes clear that worse is to come.

[1] International Shipping Federation

2.2 Present Manpower Situation

The ISF/BIMCO report [1] estimates that in 2000 there were 404,000 officers and 823,000 ratings readily available to the market and the demand was estimated as 420,000 officers and 599,000 ratings, thus indicating a small deficit in the number of officers (see Table 1).

	Demand – Offer	%
Officers	-16,000	-4%
Ratings	+ 224,000	+30%

Table 1 – Demand x Offer of Seafarers in 2000

It was also highlighted by the report that there are doubts about the extent to which the number of ratings presented have the appropriate qualifications for international service.

This small deficit of officers may already be posing a threat to the safety of life at sea, since it has been seen over the last years an increase of the number of people on board ships with false certificates of competence that are probably filling that gap (12,535 cases of forgery in certificates were revealed by an International Maritime Organisation (IMO) study in 2000)[3].

The maritime industry has already responded to this situation and the number of officer trainees has increased from 1 in 13 officers in 1995 to 1 in 10 in 2000. Nevertheless, studies indicate that the training levels still need to be increased at least to 1 officer trainee in 7 officers, meaning approximately 1.5 trainees per ship [1].

Such a target will be very difficult to achieve not only because of the costs involved but because of the difficulty in recruiting the amount of people needed, because of to the little general appeal that sea-going life now holds

[2] Baltic and International Maritime Council

all over the world [2] and for the high percentage of failure – around 30% [1] – in the Officer training process.

The new competence standards required by the IMO STCW 95[3], which will fully take effect in 2002, have also reduced the number of candidates available to occupy those training places.

Algeria	Iceland	Portugal
Antigua and Barbuda	India	Republic of Korea
Argentina	Indonesia	Romania
Australia	Ireland	Russian Federation
Azerbaijan	Islamic Republic of Iran	Saint Vincent and the Grenadines
Bahamas	Italy	Samoa
Bangladesh	Israel	Senegal
Barbados	Jamaica	Singapore
Belgium	Japan	Slovenia
Brazil	Kiribati	Solomon Islands
Bulgaria	Latvia	South Africa
Canada	Liberia	Spain
Chile	Lithuania	Sri Lanka
China	Luxembourg	Sweden
Colombia	Malaysia	Switzerland
Cote d'Ivoire	Maldives	Thailand
Croatia	Malta	Tonga
Cuba	Marshall Islands	Trinidad & Tobago
Cyprus	Mauritius	Tunisia
Czech Republic	Mexico	Turkey
Denmark*	Micronesia (Federated States of)	Tuvalu
Ecuador	Morocco	Ukraine
Egypt	Myanmar	United Kingdom**
Estonia	Netherlands	United States
Fiji	New Zealand	Uruguay
Finland	Norway	Vanuatu
France	Pakistan	Venezuela
Georgia	Panama	Viet Nam
Germany	Papua New Guinea	Yugoslavia
Ghana	Peru	China (Hong Kong SAR)***
Greece	Philippines	
Honduras	Poland	
Hungary		

* Includes: Faeroe Islands
** Includes: Isle of Man, Bermuda, Cayman Islands, Gibraltar
*** Associate Member

Table 2 – Parties included in the “White List” at 8 June 2001 [4]

The IMO regularly distributes the “White List” (see Table 2) of countries that are considered to satisfy the standards set by STCW 95. This means that a seafarer holding a certificate of competence issued by a country that failed to be included in the white list will theoretically become unemployable.

[3] International Convention on Standards of Training, Certification and Watchkeeping for Seafarers

By 08/06/2001, 94 of the 158 IMO Member States were in the "white list", indicating the inclusion of an additional 23 countries after the first edition published in 2000.

The OECD[4] countries remain the most important source for officers (see Figure 1), but the Far East and the Indian sub-continent are constantly increasing their share by approximately 4% every 5 years.

As an example, in a recent study by the European Commission [2], it was observed that the number of European Union (EU) nationals employed on board EU vessels dropped 40% when compared with the figures from 1985.

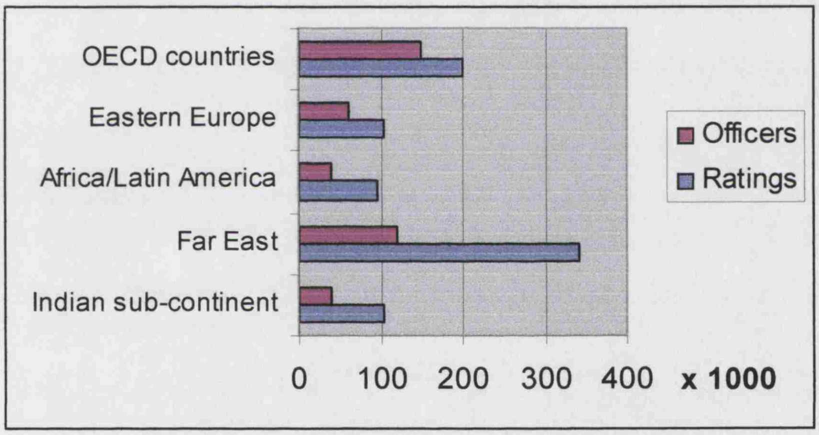


Figure 1 – Nationality Distribution of Seafarers

This information is relevant when we look at the age structure of seafarers from OECD countries, most of them occupying senior positions as Masters or Chief Engineers. In 2000, it was estimated that 40% of these officers are over 50 years old and 18% over 55.

Studies have shown that the average age for Officers is increasing at an alarming rate (see Figure 2) and that there are insufficient numbers of junior OECD officers to substitute the senior officers after their retirement and

[4] Organisation for Economic Co-operation and Development

the obvious answer would be their replacement by Asian officers, but the situation may prove to be more complicated.

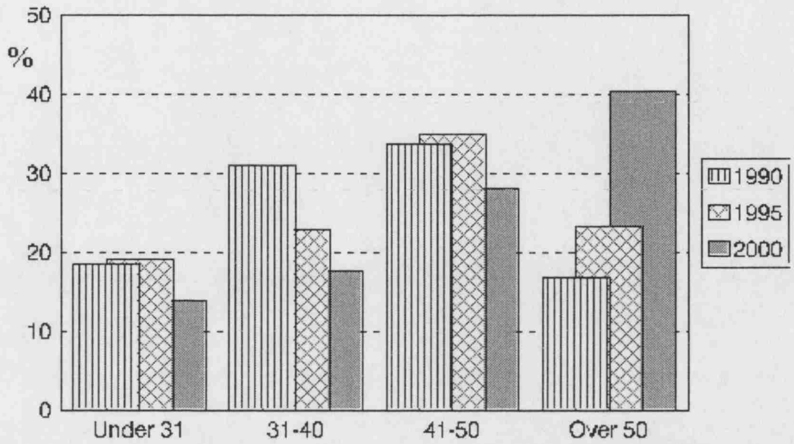


Figure 2 – Age structure of OECD officers [1]

There are some issues that can prevent surpluses from one nationality from compensating shortages from other countries, such as cultural and language incompatibilities or flag requirements, but the most important however, is the potential lack of qualified senior seafarers from outside OECD countries.

Considering the age structure of Far East Officers (see Figure 3), it can be seen that the distribution has been maintained over the last 10 years and that very few officers continue at sea after the age of 50.

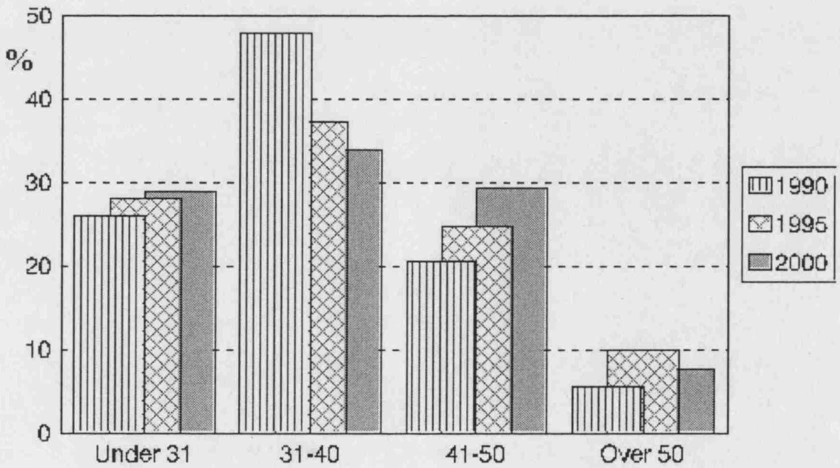


Figure 3 – Age structure of Far East Officers [1]

One explanation for this phenomenon is that these officers are very well paid for their country standards and can retire at an early age [1]. If this situation persists in the future, the assumption that Asian officers will substitute the retiring OECD officers may be challenged.

2.3 Possible Scenarios

In the report [1], a number of possible scenarios that may characterise the future balance between offer and demand of seafarers are studied, taking into account fleet growth, training levels, wastage rates and the views of senior shipping executives (see Figure 4).

One of them is said to be a realistic "benchmark" scenario, considering the observed historical growth rate of the number of ships in the world fleet in the past decade – 1% –, and assumes that recruitment and wastage levels are the same experienced over the last five years.

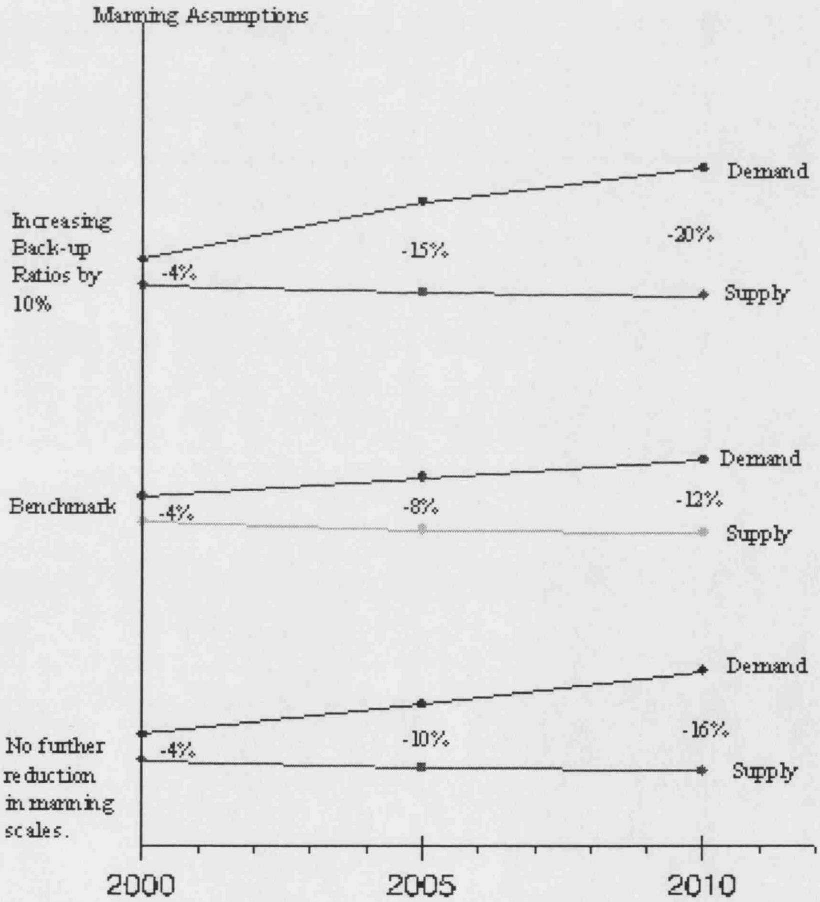


Figure 4 – Predicted Supply-Demand Gap for Officers [1]

Although the forecast is quite sensitive to a number of factors, the clear message is that the present shortfall of officers will worsen, unless action is taken.

One solution, a further increase in automation levels in order to reduce crewing levels appears to be reaching its limits. Those limits may not be related to the technology, but to the human/machine interface and the overflow of information that a crewmember has to interpret and analyse in order to make decisions and perform tasks.

This problem, together with the abnormal working hours, life style due to working shifts, limited onboard companionship and very short periods ashore are sources of stress, fatigue and psychological strain, which lower the physiological and psychological functions of the human body, affecting the effectiveness of a crew [5]. These factors and in view of recent regulations (STCW 95, ILO[5], etc) and Union requirements (e.g. ITF[6]), it is very unlikely that further reductions in manning levels will be possible.

A new approach is needed to solve this crisis and the unmanned ship concept presented in this thesis could be an attractive solution.

[5] International Labour Organisation
[6] International Transport Workers' Federation

2.4 Summary

The review of the maritime manpower situation, as discussed in this chapter, points to the following conclusions:

- Maritime manpower shortage is once more an imminent threat to the shipping industry;

- Predictions based on the observed recruitment and wastage levels and on the historical growth rate of the number of ships in the world fleet points to a supply-demand gap for Officers of 12% in 2010;

- The solutions implemented during previous crisis, such as reduction in manning levels or higher recruiting rates, are either impracticable or highly dependent on factors that industry has little or no control.

A new concept is needed to solve this crisis and the design of a totally automated unmanned ship will be discussed in the following chapters, always comparing its performance, cost and safety with state-of-the-art conventional designs.

CHAPTER 3

THE MANNING COST

3.1 Introduction

In many texts related to the introduction of automation on board ships [9], a graph, such as the one in Figure 5, is usually presented in order to show the need to increase automation levels when manning levels are reduced, so that the overall performance of the ship is not degraded.

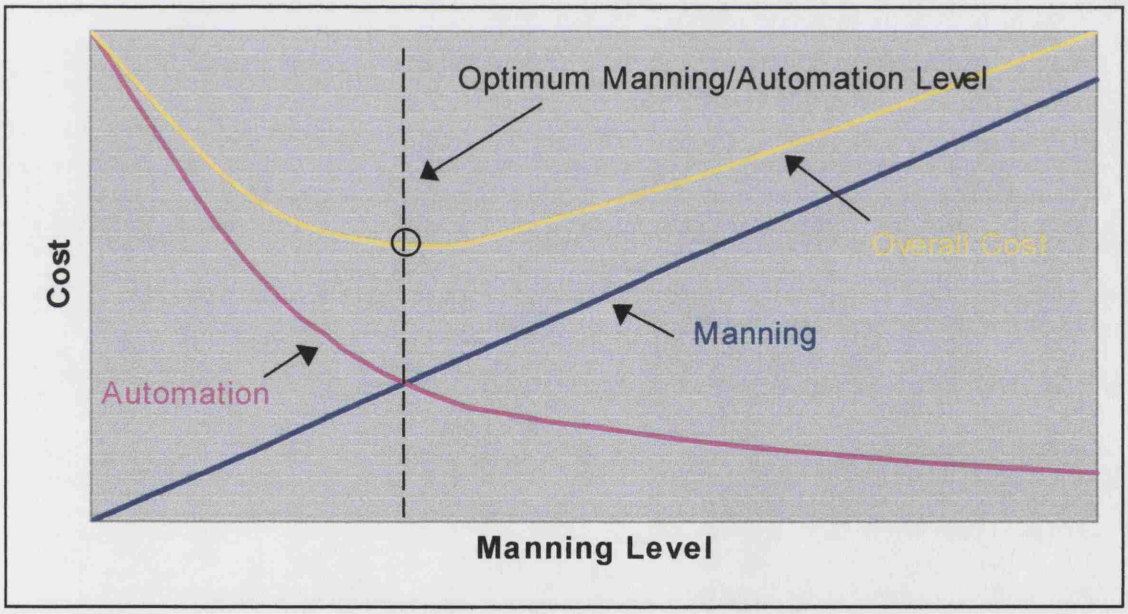


Figure 5 – Conventional Manning / Automation Level Analysis

It appears from the graph that there is an optimum balance between the level of automation and the size of the crew that results in a minimum overall cost. At this point, any further investment towards automation would not be worthwhile.

Such analysis is based on the assumption that the cost of the crew increases linearly with the number of people on board and that the cost of automation follows an exponential curve, indicating that the automation of decision making tasks is expected to be much more expensive than lower level tasks

Industry has been using this analysis since automation has been widely introduced in the 1970's and although the technology needed to increase automation levels on board ships was available or could be developed in a reasonable time, its inclusion it could not be justified for economic reasons.

The analysis however considers only part of the total cost of maintaining a crew on board a ship since it does not compute the cost of life support systems required to be fitted when there are people living on board or the maintenance costs associated with these items.

In this chapter, the manning costs are divided into "operating cost", which is that related mainly to staff remuneration and the "initial cost", relating to the equipment required on board to support the crew.

3.2 The "Operating Cost"

In the analysis, the "operating cost" will comprise of periodical expenditure related to the maintenance of a suitably qualified crew on board a ship. This would include wages and associated costs, as well as maintenance costs of life support equipment required (see Table 3).

Such items can then be subdivided into direct costs, for those elements that can be directly attributed to the wage element as well as travel, victualling and training, and the indirect costs, which will include other items commonly included on the crew agreement and the maintenance of life support systems (see Table 3).

Direct	Indirect
Basic wage	Welfare / Social payments
Overtime	Agency Fees
Leave	Communication and Bank Charges
Pension	Working Gear
Travel	Recruitment / Medicals
Victualling	Standby pay
Training	Crew Accident Insurance
Union Fees	Port Expenses
	Sick pay
	Crew-Related Equip. Maintenance

Table 3 – Operating Cost Subdivision

Most of these items, specially the direct costs, will vary depending on crew numbers, the nationality of the crew, employment agreement, local conditions, etc.

It is calculated that the highest EU wage for able seamen is some 15 times higher than the lowest non-EU wage (when social costs are included) and 5.6 times higher for chief officers [2]. Even amongst non-OECD countries, wages can differ by 100% [7].

In this study the ITF Uniform "TCC"[7] Collective Agreement 2001 [6] will be used, which is a standard agreement developed for Flag of Convenience ships and defines minimum wages, hours of duty, guaranteed monthly overtimes, leave, maximum period at sea, sick pay, etc.

It can be seen as an optimistic assumption when the current manning policy throughout the world is considered, where there is usually a mix of nationalities and, as a rule, senior officers are usually much better paid than the minimum wages set by this agreement, which can be seen at Annex 1. On the other hand, when the trend towards a non-OECD crew is considered, as discussed in Chapter 2, this assumption may become valid for a near future.

A Company's contribution to the ITF Seafarers' International Assistance, Welfare and Protection Fund of £153 per position per year [6] was also considered in addition to the values given by Annex 1.

Victualling costs will depend primarily by the size of the complement and its nationality / dietary habits, as well as the ship's trading area and the length of each journey. Typical victualling rates range from £3 to £6 per person per day [8]. A value of £5 was assumed in this study.

The different voyage lengths and the number of crew changes required in any year influence the total annual travel cost. Maximum continuous time at sea will depend on the nationality / agreement and can vary from 4 to 12 months, typically. The duration of employment set by the ITF Agreement is 9 months and this figure was used in the study, as well as a typical one-way seafarers' rebated ticket price of £350 (Europe – Far East).

Usually, seafarers are engaged through a manning agent and as a norm there will be a one-off fee plus monthly payments. A typical manning agency charges £130/person plus £100/person/month thereafter [8].

[7] Total Crew Cost Concept

With the more stringent qualification requirements posed by STCW 95 and ISM Code[8], constant training became more important than never. The training cost depends upon a number of factors such as owners' policy, employment style and quality of personnel, but as an estimate it can be assumed to be in the order of 2 – 6% of the overall manning budget [8]. A value of 5% was used in this analysis.

The maintenance of the equipment required for the habitability, safety and welfare of the crew was also estimated from figures provided by shipping companies. An average value of £48,000 per year was assumed for any ocean going ship [95].

The cost of the remaining items listed in Table 3 depend on a number of factors that makes it very difficult to quantify and a suitable margin was assumed, based on reported manning costs by 3 Quays Marine Services on March 2000 [95].

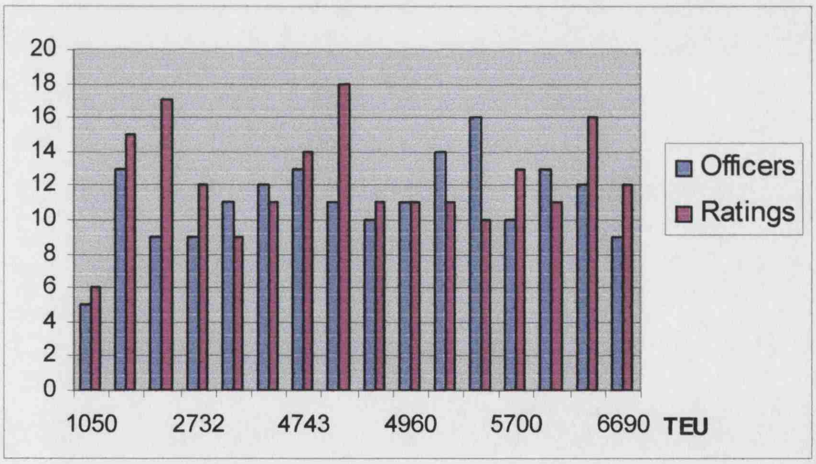


Figure 6 – Current Manning Levels on board Containerships

A survey based on "Significant Ships" from 1995 to 2000, concentrating exclusively on containerships with similar automation levels showed that there is not a clear relationship between the number of people on

[8] International Safety Management Code

board and the cargo capacity of the ship, represented by the number of TEU[9] (see Figure 6).

There is no international convention regarding the minimum required complement for any given ship and this number is usually defined by the Flag State, based on different national regulations.

The final number of people on board also will depend on the owner's policy and it is very common to find Crew Lists with far more seamen that that required by the Safe Manning Document, including trainees and repair parties.

Due to this lack of standardisation, the ITF Uniform "TCC" Collective Agreement was used to define the size of the crew, given the Gross Tonnage of the ship and its automation level. Examples of these proposed manning scales are listed at Annex 2.

30 person complement

Wage+Overtime+Leave+Pension	=	£439,460
Victualling	=	£51,100
Travel	=	£37,333
Agency Fees	=	£42,000
Training	=	£9,130
Crew Related Equip. Maintenance	=	£48,000
Other	=	£52,173
TOTAL / Year		**£679,197**

15 person complement

Wage+Overtime+Leave+Pension	=	£239,306
Victualling	=	£25,550
Travel	=	£18,667
Agency Fees	=	£21,000
Training	=	£4,565
Crew Related Equip. Maintenance	=	£48,000
Other	=	£26,087
TOTAL / Year		**£383,175**

Figure 7 – Examples of Operating Cost Calculations

[9] Twenty Foot Equivalent Units

ITF proposed manning levels and current practice as shown in Figure 6 indicate that modern ocean going ships have a total complement ranging from 15 to 30 seamen and manning costs were estimated in that range.

Figure 7 shows examples of calculations for the limits of 15 and 30 person complements.

Considering a life span of 25 years, the manning operating cost through the life of ship could be calculated for different complement sizes between 15 and 30, being extrapolated for lower crew sizes and Figure 8 shows the results.

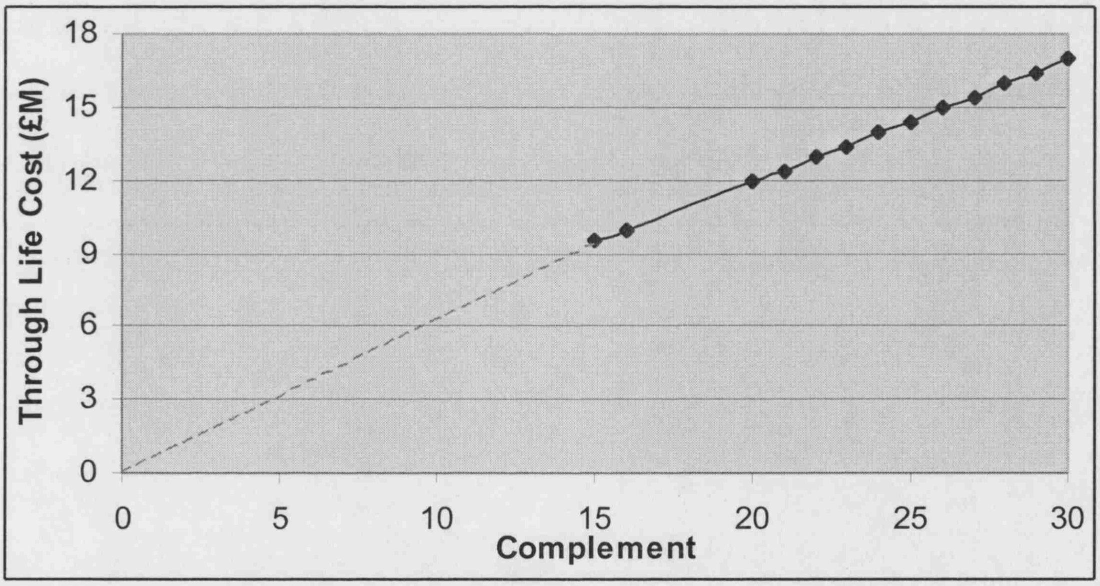


Figure 8 – Manning Operating Costs over 25 Years

This cost is very significant when compared with other operating costs, such as:

- Insurance;
- Repair & Maintenance of systems not related to the crew; and
- Dry Dock Accrual.

Figure 9 gives an idea of a typical operating costs distribution, based on Drewry Consultants [7] and 3 Quays Marine Services [95] data.

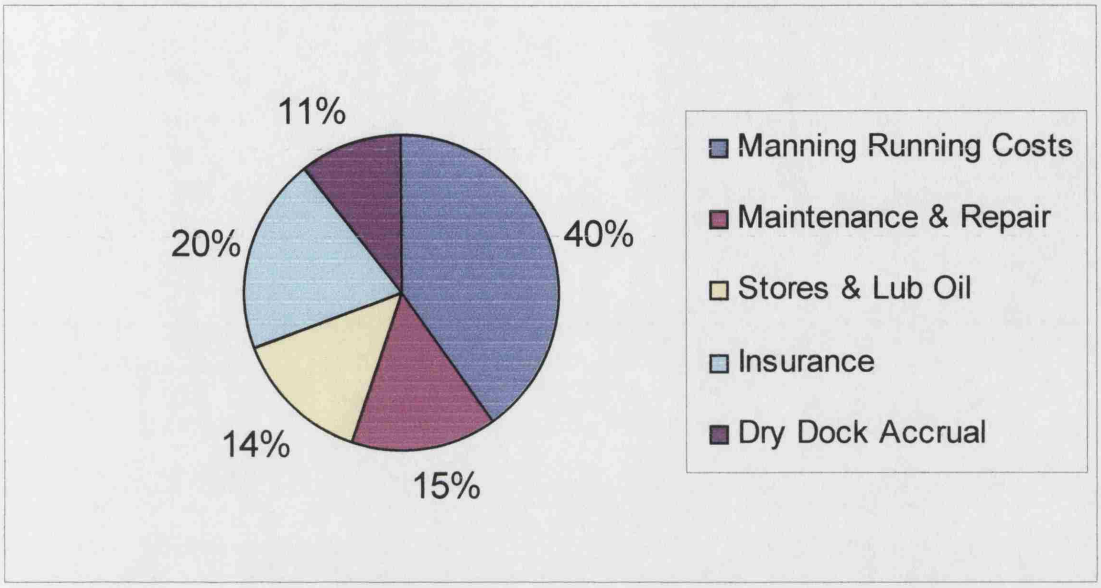


Figure 9 – Typical Operating Costs Distribution

3.3 Initial Cost

The part of the cost of having a crew on board a ship that is not considered in the economic analysis of the balance between manning and automation levels is that related to the initial building and installation costs of the equipment required to provide safety and welfare to the crew.

This cost is not restricted to the money invested in the equipment but is also reflected on the volume and weight added to the ship, meaning that less cargo can be transported.

Based on data available in the UCL Ship Design Data Book, some manufacturers' data and ILO minimum requirements, the volume, weight and cost of the following items were estimated for complements ranging from 15 to 30 seamen:

- Cabins;
- Offices;
- Lavatories / Changing Rooms;
- Passages / Stairs associated with accommodation spaces;
- Dining salon / Lounge / Messes / Recreation room;
- Wheelhouse / Chartroom;
- Galley;
- Laundry;
- Refrigerated and General Stores;
- Structural elements related to the items above;
- Air conditioning (for living spaces);
- Waste management equipment;
- Desalination plant and fresh water distribution (for crew consumption); and
- Life saving equipment.

Annex 3 shows a sample calculation for a 10 person complement ship (4 officers and 6 ratings) and Figure 10 shows how this initial cost vary with the number of seamen on board, including an extrapolation for the minimum theoretical crew of 3 members, when working shifts would still be possible.

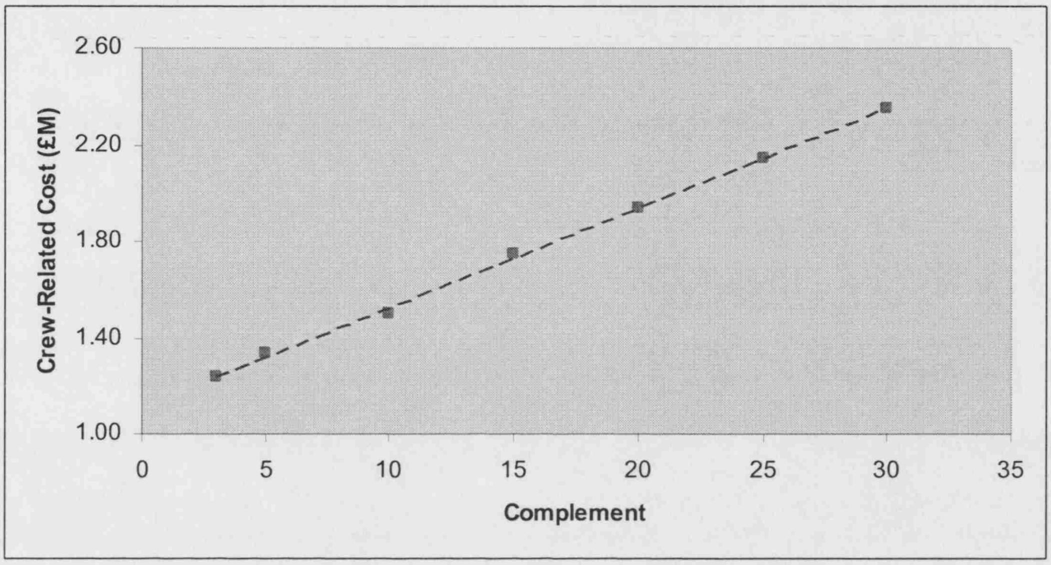


Figure 10 – Crew-Related Initial Cost

This cost can represent a significant percentage of the total building cost of a ship, especially when smaller vessels are considered, where the crew-related initial cost may represent up to 25% of the total cost.

3.4 The Total Manning Cost

From the calculations performed in the previous items of this chapter, the total manning cost can be evaluated for different complements.

The graph shown in Figure 11 presents a new possibility to achieve a minimum cost with the balance of manning and automation levels, in addition to that seen in Figure 5, which will always point to a non-zero complement.

normally.

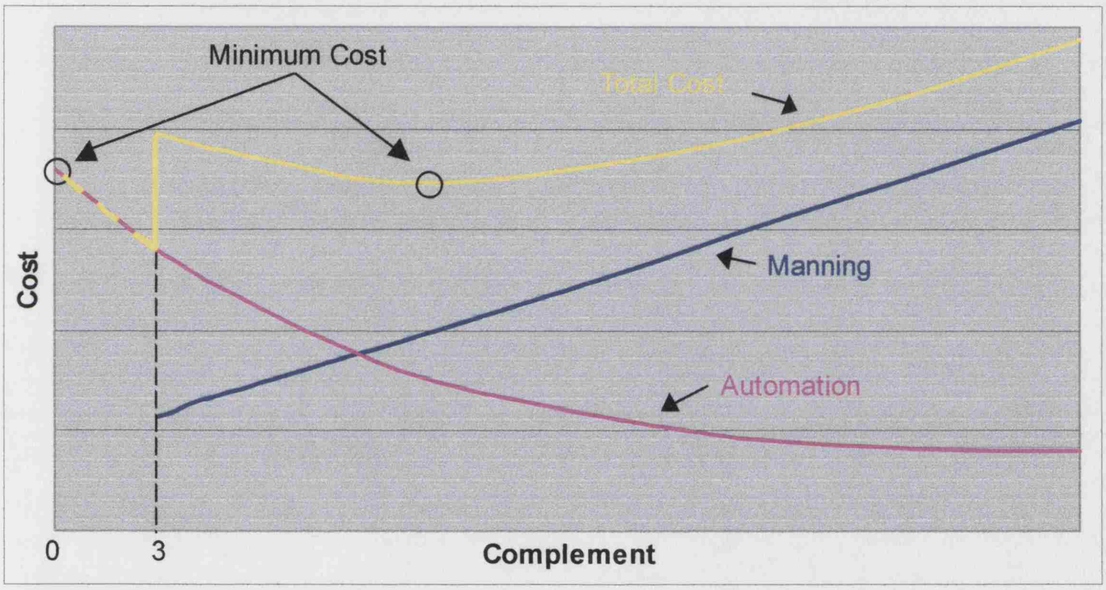


Figure 11 – A New Manning / Automation Level Balance

It becomes clear that, depending on the shape of the automation curve, an unmanned ship could present the minimum overall cost, considering that a complement of 1 or 2 seamen would not allow reasonable working shifts.

From the calculations shown at Annex 3, it can also be noted that the total weight of the crew-related items is irrelevant when compared to the displacement of an ocean going ship.

On the other hand, the volume required by these systems could represent an increase in the cargo capacity of the ship, especially when the cargo is stowed on the deck, since most of the crew-related volume is usually located in the superstructure.

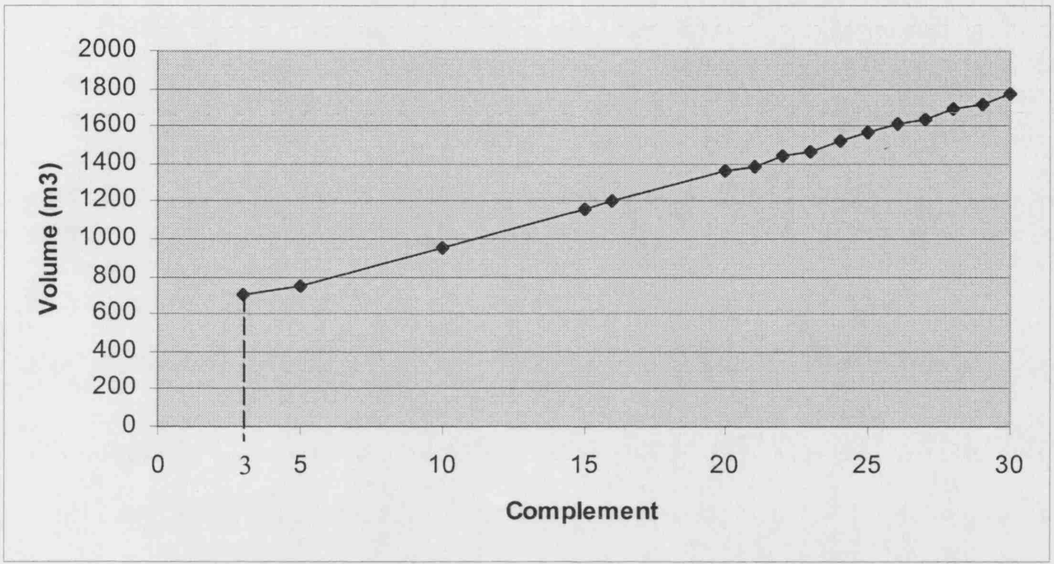


Figure 12– Volume Required by the Crew

When current manning levels are considered as shown in Figure 6, a budget between £12M and £20M through 25 years becomes available for the automation and additional equipment needed to substitute the entire crew on board a ship.

In addition to that, volumes in the range of at least 1200 – 1800 m^3 would become available for any extra equipment needed or for increasing the cargo capacity of the ship, mainly above the main deck.

These numbers speak for themselves and the potential advantages of an unmanned ship become even clearer.

3.5 Summary

The following conclusions can be drawn from the total manning cost calculations performed in this chapter:

- Manning "operating costs" can represent 40% of the total operating cost of a vessel;

- Initial building and installation costs of equipment required to provide safety and welfare of the crew, defined as the "manning initial cost" can represent up to 25% of the total building cost of a ship;

- When the "manning initial cost" is considered in the economic analysis of the balance between manning and automation levels, it is theoretically possible to obtain a minimum cost for an unmanned ship;

CHAPTER 4

NAVIGATION

4.1 Introduction

A number of new technology advances in the area of marine navigation have emerged in the past years, mainly focused on relieving the crew of routine activities and making better information available to ship's masters and pilots [11].

What can be noticed is that these technologies, although widely contributing to the reduction of the navigation watch, still rely on the presence of a "human link" to integrate the system, but if they are used with a different philosophy, the human link could be removed from the bridge.

For the purpose of the study, marine navigation has been divided in this chapter into the following major areas:

- Position Fixing;
- Collision Avoidance;
- Route Planning.

Initially, the different phases of marine navigation are identified and the performance requirements for each of these phases are defined and compared with technologies currently available.

The risks associated with the reliance on systems controlled by third parties and the vulnerability of those systems are analysed in order to determine the need of incorporating redundant and back-up equipment to the system.

Finally, a survey of the technology and procedures needed to automate the navigation of an ocean-going ship and its limitations are presented and a complete system is outlined in order to cover the main tasks in the field of navigation and related operations.

4.2 Position Fixing

4.2.1 Marine Navigation Phases and Requirements

For the purpose of this analysis, marine navigation will be divided in three major phases identified as:

- **Ocean navigation** is when a ship is beyond the continental shelf (200 meters in depth), and more than 50 nm[10] from land, in waters where visual reference to land or to fixed or floating aids to navigation is not practical and that are sufficiently far from landmasses so that the hazards of shallow water are expected to be nil.

- **Coastal navigation** is that phase in which a ship is within 50 nm from shore or the limit of the continental shelf (200 meters in depth), where a safe path of water at least one mile wide, if a one-way path, or two miles wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interport traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routing systems and scientific or industrial activity on the continental shelf are encountered frequently in this phase of navigation.

- **Harbour entrance and approach navigation** is conducted in waters inland from those of the coastal phase and begins generally with a transition zone between the relatively unrestricted coastal waters and the narrowly restricted waters near and/or within the entrance to a bay, river, or harbour, where the navigator enters the harbour phase of navigation. Usually, harbour entrance requires navigation of a well-defined channel, which vary from 100 to 600 meters in width, and frequent manoeuvring of the vessel to avoid collision and grounding. This phase ends when the ship is brought up within a range of around 300 meters from the berthing line.

There is no universal requirement for position accuracy (or acceptable error) in marine navigation and it depends very much on the application and the size of the vessel, as well as the particular geographic and traffic characteristics of the area.

Textbooks, recent papers [12] and some national requirements [13] tend to propose an accuracy level sometimes unachievable by the majority of ships now in service, specially in restricted waters, but those levels will be the benchmark for this work.

For ocean navigation, the requirements must provide the vessel with a capability to avoid known hazards in the ocean (small islands, reefs, etc) and to approach land or restricted waters. Continuous availability of accurate position fixes may also be required in order to enable the vessel to follow a pre-defined route and a minimum accuracy (2 drms[11]) of 2 nautical miles will be required, although 1 nautical mile is desirable. Ideally, the vessel's position should be determined every 15 minutes or less, but a fix interval of as long as two hours may be acceptable.

For the coastal phase, where vessels may need to navigate within the designated one-way traffic lanes at the approaches to many major ports, in fairways established through offshore oil fields, and at safe distances from shallow water, an accuracy of at least 0.25 nm will be required for fixes obtained every minute or less.

---

[10] Nautical miles

[11] Distance root mean square - the radius of a circle that contains at least 95 percent of all possible fixes that can be obtained with a system at any one place.

Radio navigation conferences have indicated that for many mariners not familiar with modern ECDIS[12] systems, the radio navigation system becomes a secondary tool when entering the harbour entrance and approach environment [13], since for the safe navigation, a highly accurate verification of position is needed almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the vessel should steer.

An accuracy of 5 to 20 meters, depending on the circumstances, with fix updates every 5 to 10 seconds would certainly provide a very consistent navigation solution even for the most restricted waterways.

Phase	Accuracy	Fix Interval
Ocean	1 – 2 nm	15 min – 2 hours
Coastal	0.25 nm	1 minute
Harbour Entrance	5 – 20 meters	5 – 10 seconds

Table 4 – Maritime Operation Performance Requirement

As can be seen in Table 4, the position fixing requirements can vary sharply depending on the phase of marine navigation in which the vessel is involved and suitable equipment and procedures should be investigated for each of the situations.

An accurate, reliable and timely position determination is the basis of all navigation tasks and the technological evolution in this field in the past 10 years has been quite remarkable.

The predicted introduction and phasing out of the main radio navigation systems can be seen in Figure 13, and it becomes clear that satellite navigation will be the system of choice in the years to come and therefore, will be discussed in the following sections.

[12] Electronic Chart Display & Information Systems

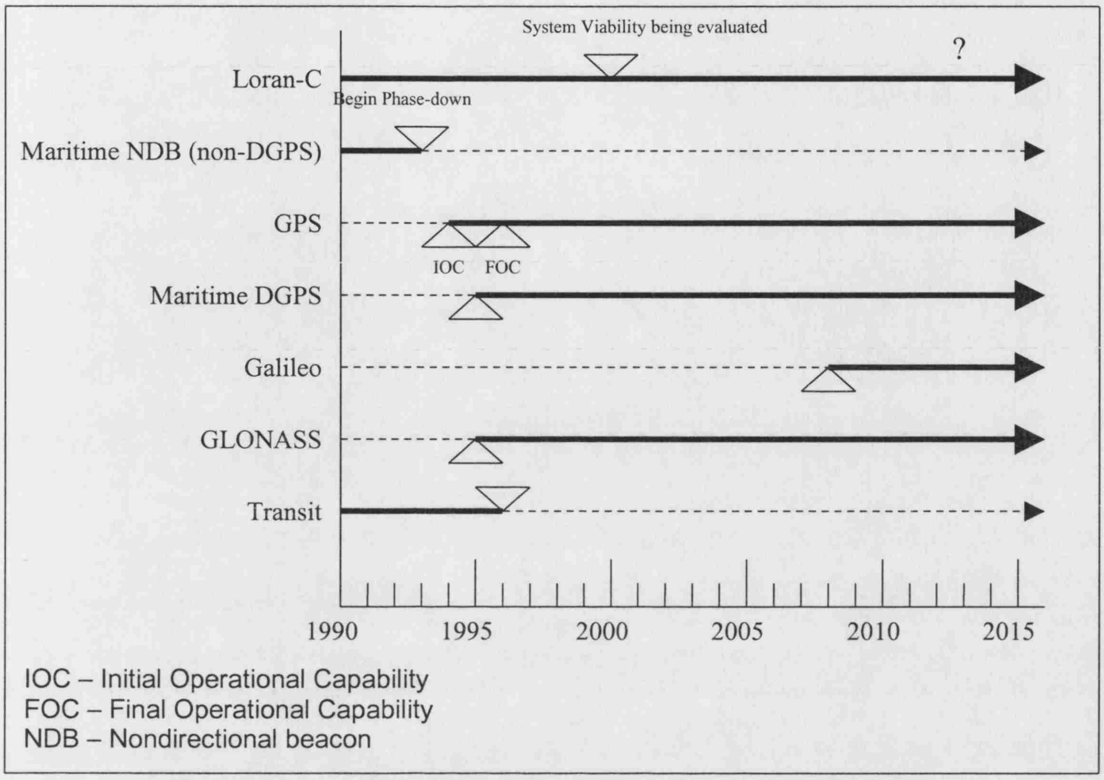


Figure 13 – Radio Navigation Systems Operating Plan

4.2.2 Satellite Navigation Systems

Satellite navigation became available to civilian use in the 1970's and was not designed to replace other electronic aids, since depending on the area of the globe, the ship would only receive a fix every 4 to 6 hours, meaning it would only be useful at blue water transits in certain areas.

It was only in the mid-1990's, however, with the widespread of the Global Positioning System (GPS), that most marine users have started to migrate from Radiobeacon direction finding, Loran-C and Transit as their primary electronic navigational aid (See Figure 14).

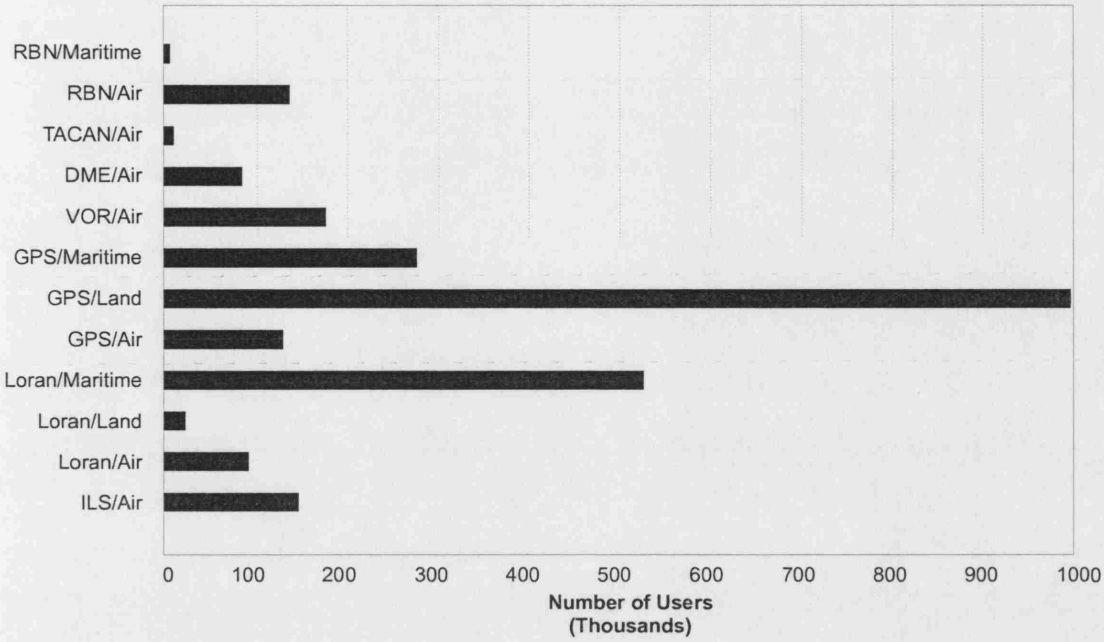


Figure 14 – Estimated U.S. Radio Navigation System User Population [13]

1999

4.2.2.1 Global Positioning System (GPS)

The GPS, developed and controlled by the U. S. Department of Defence, is a worldwide, all-weather radio navigation system consisting of 24 satellites and their ground stations.

The Standard Positioning Service (SPS), which is unrestricted for civilian users, was subject to an intentional error into satellite clock and ephemeris parameters, which degraded user performance until May 1, 2000, the so-called Selective Availability (SA).

This degradation introduced a position error of 100 meters (2 drms) which is now around 10 – 30 meters due to a number of other error sources, such as [14]:

- Noise errors – 2 meters;
- Satellite clock errors uncorrected by the Control Segment – 1 meter;

- Uncorrected ephemeris data errors, caused by gravitational pulls from the moon and sun and by the pressure of solar radiation on the satellites – 1 meter;

- Tropospheric delays caused be changes in temperature, pressure and humidity associated with weather changes – 1 meter;

- Ionosphere delays – 20 meters;

- Multipath caused by reflected signals from surfaces near the receiver – 0.5 meter

A complete analysis of the performance standard of the GPS service after the discontinuation of the Selective Availability can be found in Reference [16], but Figure 15 gives an idea of how the accuracy levels were increased.

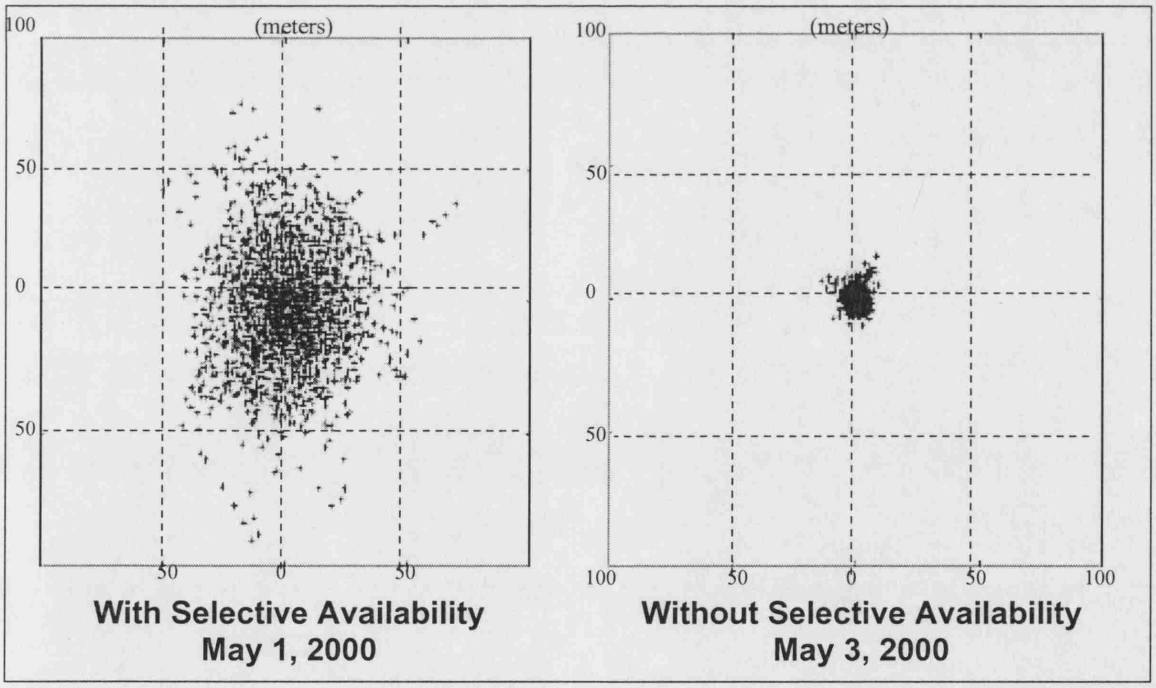


Figure 15 – Comparison of GPS Fixes With and Without Selective Availability (Full 24 Hour Data Sets) [15]

4.2.2.2 GLObal NAvigation Satellite System (GLONASS)

Another satellite navigation system exists besides GPS and that is the Russian GLONASS. The development and build-up of the two systems has been similar but for GLONASS the maintenance of the system has been scarce resulting in a declining number of operational satellites.

The GLONASS constellation has been fairly stable lately with 10 orbiting satellites from the 24 that should compose the system. However, outages have been observed in a way that the usable constellation is usually reduced to nine or eight. The launch of new satellites is uncertain but a three-satellite launch took place on October 13th, 2000 after having being postponed several times [17].

On the other hand, GLONASS has some advantages over GPS, since the intentional degradation of the civilian navigation code was never part of the system. This advantage disappeared when the discontinuation of the Selective Availability was announced for GPS. However, GLONASS still has an advantage posed by a higher inclination of the satellite orbits, implying better satellite availability at higher latitudes.

Accuracies in the order of 57 to 70 meters 2 drms can be achieved with the use of the GLONASS system, as shown in Figure 16.

As could be seen, some of the characteristics of GLONASS are very similar to GPS, but there are significant technical differences. In addition, the institutional capability necessary to support the GLONASS space and control segment is significantly less than in the case of GPS.

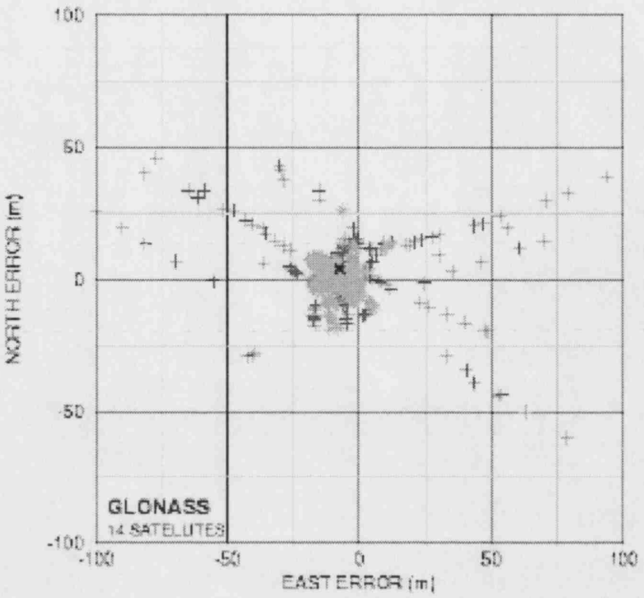


Figure 16 – GLONASS Position Fixes (1 minute sample) [18]

Yet to dismiss GLONASS as a serious candidate for satellite positioning technology because it cannot compete with GPS technology is too simplistic an analysis. Although GLONASS has the potential to rival GPS in coverage and accuracy, this potential is unlikely to be realised in the medium term, and hence for the foreseeable future GLONASS should be considered a complementary system to GPS [21].

4.2.2.3 GALILEO

GALILEO will be the European Global Navigation Satellite System (GNSS), consisting of a constellation of up to 30 satellites and its associated ground infrastructure, which unlike GPS and GLONASS systems will be under civilian control.

As can be seen in Table 5, the development plan for the European system expects that GALILEO will be fully operational by 2008.

Phase / Milestone	2000	2001	2002	2003	2004	2005	2006	2007	2008
Definition	■								
Design & Development		■	■	■	■	■			
Deployment							■	■	
System Validation				■	■	■	■	■	
Mission Validation							■	■	■
Early Operations							■	■	
Full Operations									■

Table 5 – Galileo Development Schedule [19]

A primary objective is for GALILEO to provide its services autonomously, thus avoiding any form of dependence or common modes of failure with other satellite navigation systems. On the other hand, GALILEO is being designed to be interoperable with other existing satellite navigation systems, leading to enhanced service performance resulting from the combined use of the different systems.

Furthermore, GALILEO will aim to achieve levels of performance comparable to those of other satellite navigation systems, thus providing a high level of inherent redundancy.

One advantage over GPS and GLONASS will be the availability of two navigation signals to the open and commercial services, separated in frequency in order to allow the fulfilment of precise ionospheric measurements by differentiation of the ranging measurements made at each frequency. A third navigation signal separated in frequency from the two above signals is intended for supporting the development of precise local area elements, based on the use of Three Carrier phase Ambiguity Resolution techniques (TCAR).

The basic GALILEO navigation service, the Open Service, will provide positioning, navigation and timing signals that can be accessed free of direct charge with expected performances given in Table 6.

Type of Receiver	Carriers	Single Frequency	Dual-Frequency
	Ionospheric correction	Based on simple model	Based on dual-frequency measurements
Coverage		Global	
Accuracy (95%)		H: 15 m V: 35 m	H: 4 m V: 8m

Table 6 – Service Performance for GALILEO Open Service

4.2.2.4 Satellite Augmentation Systems

The accuracy levels available from the satellite navigation systems discussed in the previous section are more than enough for the mid-ocean and coastal phases of the determination of a vessel's position, but the harbour approach requirements would not be satisfied.

Shortly after the full operation capability of the GPS was declared by the United States, base stations throughout the world started to continuously broadcast, sometimes using marine radio navigation beacons already available in the area, the corrections that should be applied to each satellite signal, compensating the majority of the existing error sources.

The principle used is to compute at a base station the difference between the position determined through satellite signals and its known position.

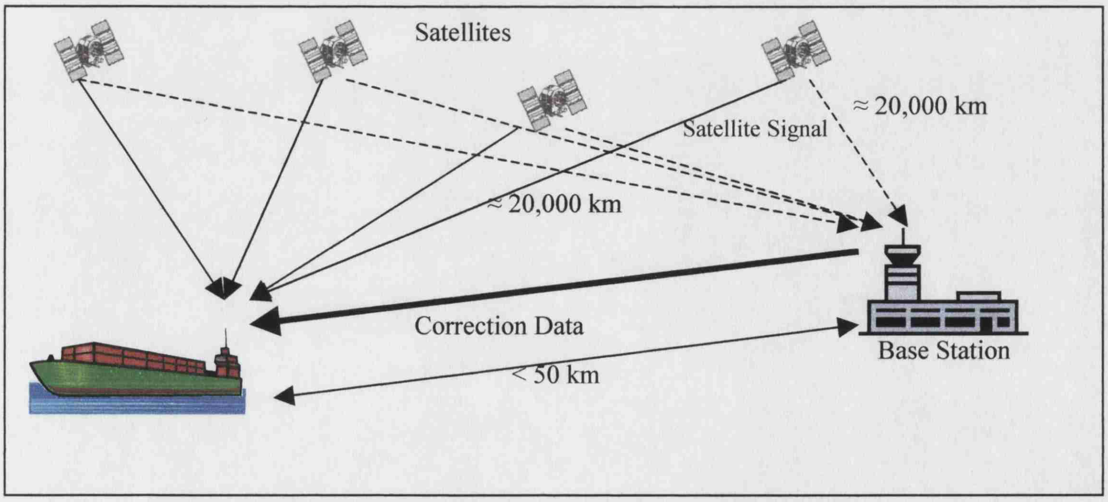


Figure 17 – Differential Satellite Navigation

Considering that the signal paths between the satellites and the base station or the ship are almost the same, since the satellites are at around 20,000 km from Earth, those differences can be broadcasted by the base station and used by satellite receivers on board, as shown in Figure 17.

This technique is called Differential Satellite Navigation (DGPS, DGLONASS or DGALILEO) and can provide accuracy in the order of 1 – 10 meters within about 30 miles of the base station, fulfilling the requirements for the harbour approach phase.

To make the power of DGPS or DGLONASS universally accessible, navigation authorities in many countries are creating systems to supply differential corrections over a wide area. Originally developed for aviation, the systems are also suitable for terrestrial and in-shore marine use and are available to anyone with an enabled receiver.

Currently operating or proposed systems include the Wide Area Augmentation System (WAAS) in North America, the European Geostationary Navigation Overlay System (EGNOS) in Europe, the Multifunctional Transport Satellite-based Augmentation System (MSAS) in Japan, and the Satellite Navigation Augmentation System (SNAS) in China. They are collectively known as Wide Area DGPS (WADGPS) or Satellite-Based Augmentation Systems (SBAS) and are now in the following status [20]:

- **WAAS**: Now available for non-aviation uses on two satellites. Full operation expected by end of 2003.

- **MSAS**: First geostationary satellite expected to be up mid-2002.

- **EGNOS**: Currently broadcasting a test signal from one satellite. Full operation expected late 2004.

- **SNAS**: Two geostationary satellites up; testing in progress.

- **Australia**: The Ground-based Regional Augmentation System (GRAS) will broadcast corrections on VHF.

- **Other countries developing or investigating WADGPS systems**: Chile, Argentina, Indonesia, Singapore, India, South Korea

In a WADGPS system, a network of reference receivers combines to create a model of the best differential correction for a wide area. Geostationary satellites then broadcast this correction in the same band that regular navigation satellites use. The result is a correction that can be deciphered by any WADGPS-enabled receiver without the need for additional antennas or receivers.

WADGPS systems will improve upon the satellite navigation system by supplying enhanced accuracy, availability, and integrity.

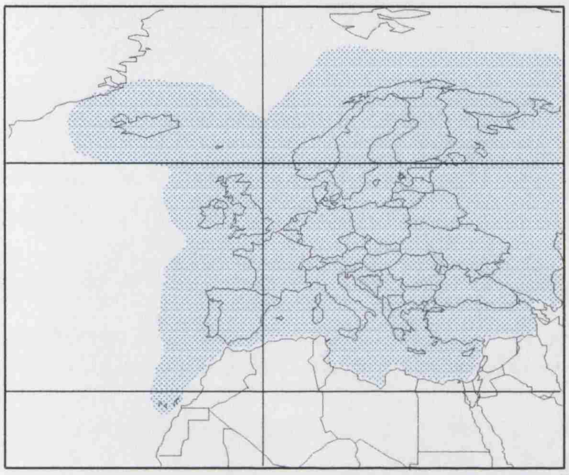
- Accuracy is the difference between the measured position and the true position and will be enhanced by supplying differential corrections over a wider area.

- Availability is the coverage of the system in time and space. To enhance availability, WADGPS geostationary satellites will also broadcast a GPS-like ranging signal.

- Integrity is the health of the system. Information about whether each satellite is functioning properly will also be transmitted by the WADGPS system that will constantly monitor navigation satellites.

An extra advantage of satellite-based WADGPS appears when we consider that the low frequency signals broadcasted from ground-based stations are more susceptible to radio frequency and weather interference, and they have a limited range. Satellite signals, since they are high frequency are less susceptible to this kind of interference and will provide greater position accuracy over a large contiguous geographic area.

As an example, EGNOS proposed coverage and characteristics are shown in Figure 18.



Horizontal accuracy	100-10m	10m
Coverage	Oceanic waters (Distance to the coast greater than 50NM).	Coastal waters (Distance to the coast less than 50NM.)

Figure 18 – EGNOS Characteristics

4.2.2.6 Vulnerability of Satellite Navigation Systems

The vulnerability problem associated with the satellite navigation systems (GPS, GLONASS and GALILEO) is mostly caused by the low power in which they transmit their signals, making them easily affected by external factors.

In this section, mainly based on Reference [26], an overview of the key factors that may affect satellite navigation systems will be discussed, as well as the expected effects and how they can be mitigated.

Mechanisms to disrupt navigation satellite signals may be divided in the following categories:

- Unintentional: ionospheric effects, interference of other radio frequency sources and signal blocking;

- Intentional: jamming, spoofing, meaconing and other deliberate effort to disrupt the navigation systems that should be seriously considered, especially in view of the recent terrorist attacks in the USA.

These mechanisms will be briefly discussed in the following paragraphs.

a) Ionospheric Interference

The first effect called scintillation is the refraction of the satellite signals, causing a delay of these signals, which can generate errors of up to 20 meters during solar events.

Dual frequency receivers, however, can measure and virtually eliminate this effect, since the delay is inversely proportional to frequency squared.

On the other hand, in areas near the poles ($\pm 65^{o}$ latitudes) and at $\pm 15^{o}$ latitudes, rapid fluctuations of the ionosphere can be observed, causing loss of lock if those changes exceed the receiver's tracking loop dynamic capability.

This effect can lead to a significant degradation of the accuracy of differential satellite positioning systems (e.g. DGPS) near these susceptible zones.

b) Unintentional Radio Frequency Interference

A number of radio frequency transmitters have been identified as potential sources of unwanted signal power in navigation satellites signals, such as:

- Broadcast television at channels 23, 66 and 67;

- Mobile and fixed VHF transmitters;

- Personal Electronic Devices (cellular telephones and two-way pagers);

- Mobile Satellite Service (MSS) communications system (Iridium, Global Star, etc.);

- Ultra Wideband radar and communications.

The use of multiple and sufficiently separated frequencies by the GALILEO system will make it extremely unlikely that an unintentional interfering source will jam all them simultaneously.

The GPS Modernisation Programme [27] will also contribute to the mitigation of unintended interferences, with a second civil signal expected to achieve Initial Operational Capability (IOC) during 2007 and Final Operational Capability during 2011.

A third civil signal is also expected to be implemented, with predicted IOC in 2012 and FOC in 2014.

c) Signal Blocking

Many analyses have shown that while DGPS positions may be available under moderate to extreme masking conditions, they are often unreliable (the position may be corrupted by an undetected blunder in the observations). In order to make the resulting position both available and reliable, DGPS must be augmented with a combination of constraints and other satellite navigation systems [25].

The quality of the satellite position fix depends upon the Geometric Dilution of Precision (GDOP), inversely proportional to the volume of the shape described by the unit-vectors from the receiver to the satellites used in a position fix as seen in Figure 19.

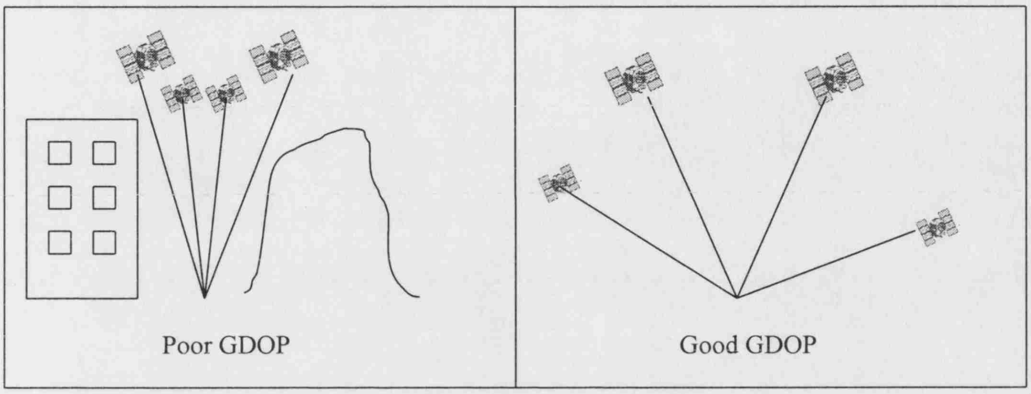


Figure 19 – Geometric Dilution of Precision

In the case of horizontal positioning (Latitude and Longitude), the term Horizontal Dilution of Precision (HDOP), one of the components of the GDOP, is commonly used. Usually receivers consider a position as valid if HDOP ≤ 2.

In restricted waters or narrow channels, the line-of-sight of satellite signals are often masked by obstructions, resulting in degraded geometry and accuracy and even unavailability or unreliable positions.

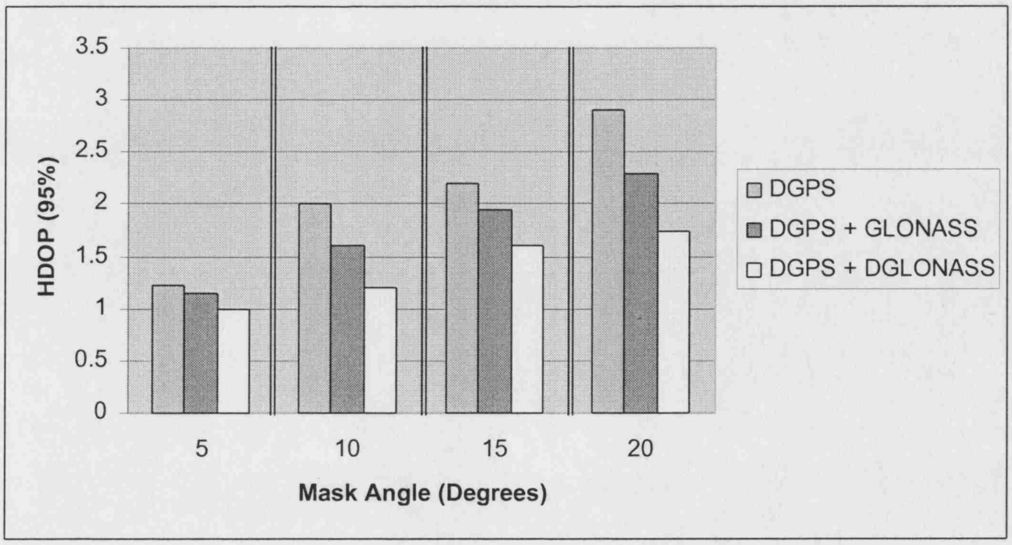


Figure 20 – GPS + GLONASS – HDOP

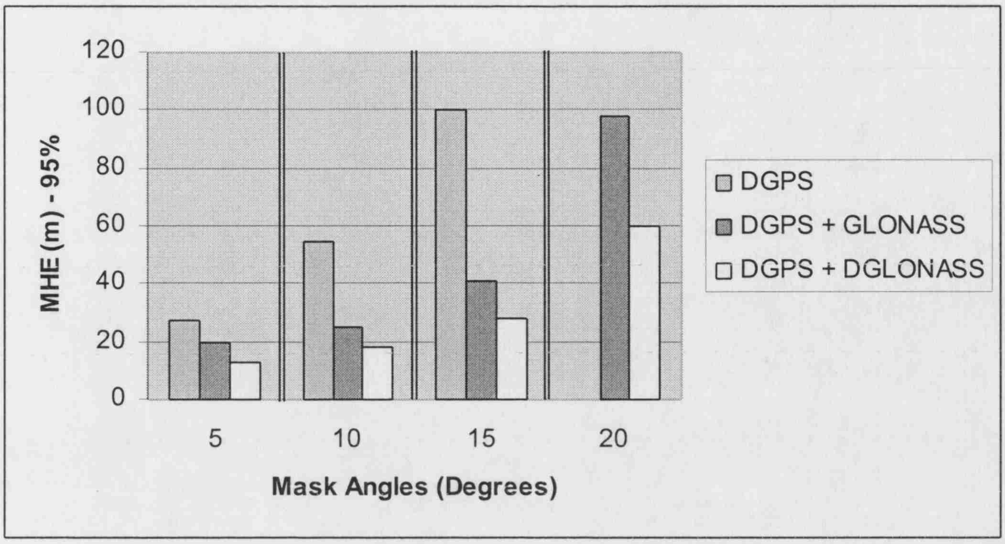


Figure 21 – GPS + GLONASS – MHE

The use of combined satellite systems results in a dramatic increase in the number of satellites available above the horizon.

Figure 21 and Figure 21[24] indicate how the availability, given by the HDOP, and reliability, given by the maximum horizontal error (MHE), are improved when 15 GLONASS satellites are used as a complement to DGPS position fixes.

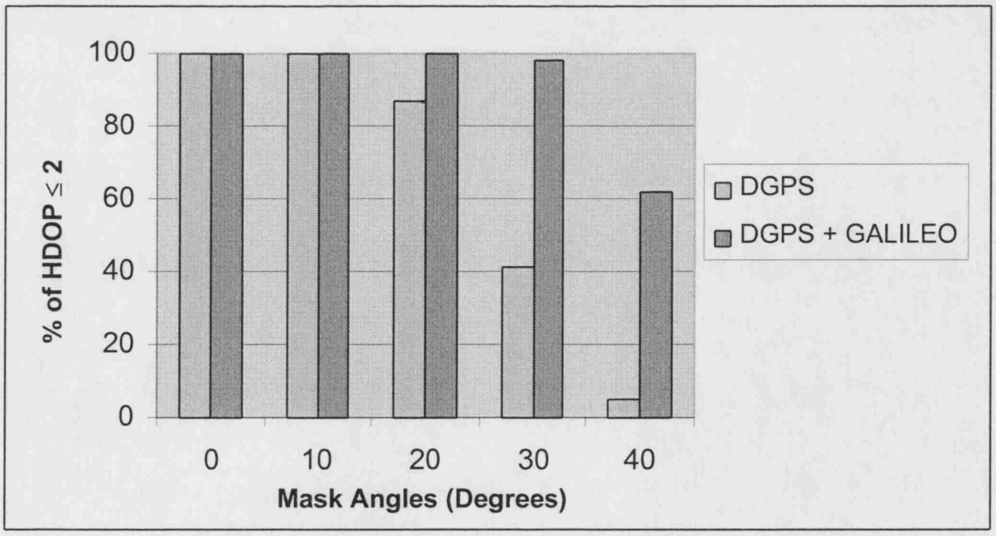


Figure 22 – GPS + GALILEO – HDOP

The same simulation can be made for the integration of GPS with GALILEO and even better results will be achieved, as shown in Figure 23 and Figure 23 [25].

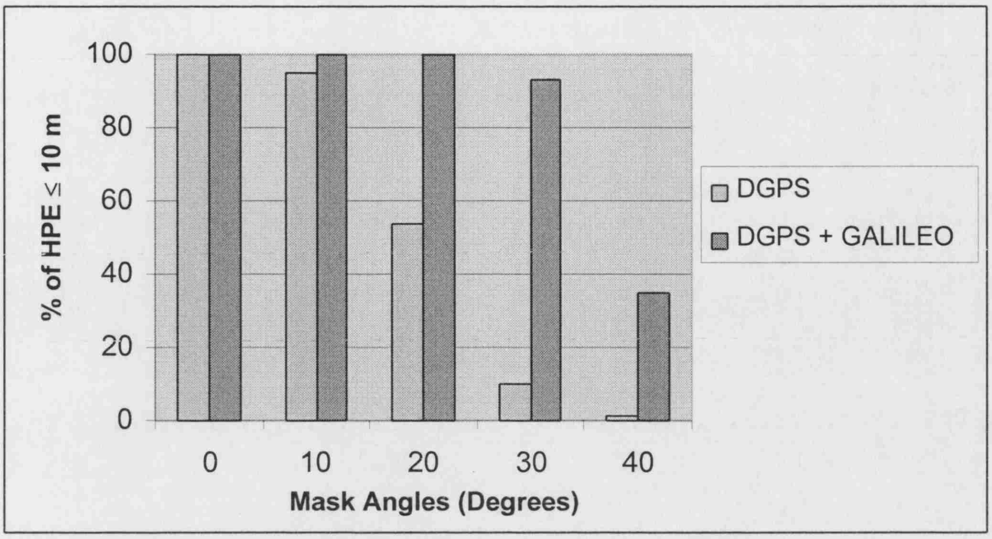


Figure 23 – GPS + GALILEO – HPE

DGPS will meet the availability and reliability requirements for most applications under masking conditions < 10°. Augmenting DGPS with Galileo, most of the availability and reliability requirements can be met for isotropic masking angles < 30°. When extreme mask angles of more than 40° are encountered the 95% HPE is in the 30-40 m range and, although the improvement achieved by including GALILEO satellites is remarkable, the system will not perform satisfactorily.

d) Jamming

Intentional interference or jamming is achieved by the emission of radio frequency energy with sufficient power and proper characteristics to prevent satellite receivers from tracking the navigation signals and sometimes leading to inaccurate position fixes.

Additional frequencies provided by GALILEO and those planned for GPS, as seen in Figure 24 may be of some effectiveness against intentional jamming, making it more difficult and costly, but not impossible.

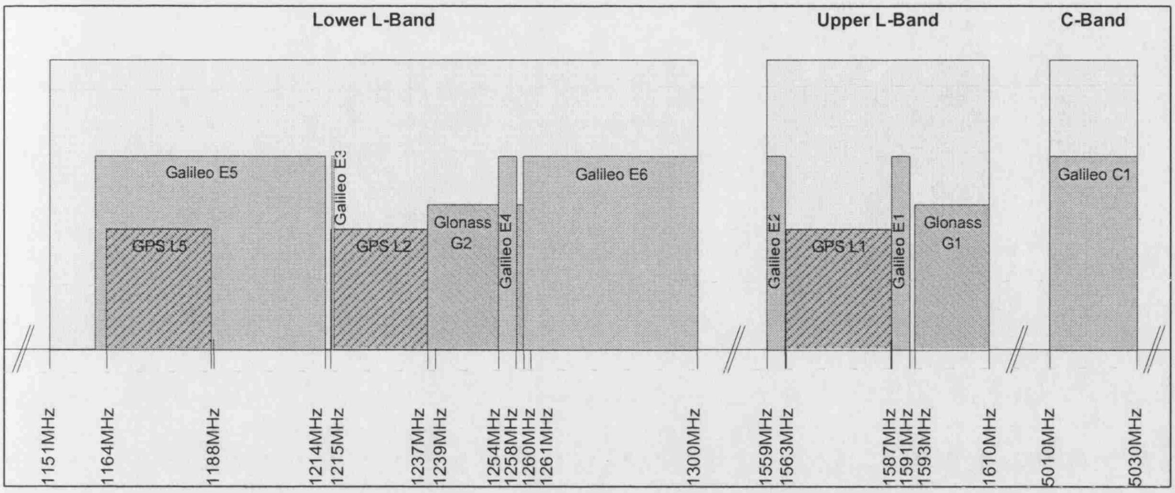


Figure 24 – Frequency Allocations [19]

One possible solution for this problem is to use the Public Regulated Service offered by GALILEO, which will be restricted to EU and other participating States authorised by Member States and is designed to be robust, so as to be resistant to interference, jamming and other accidental or malicious aggressions.

This service will have dedicated frequencies, with encryption possibly based on governmental key management, to provide the capability for greater continuity of service placed under EU and Member States Governments control for public applications devoted to European and/or National Security, some regulated or critical energy, transports and telecommunications applications and economic and industrial activities that are deemed of strategic interest for Europe [19].

The use of anti-jamming equipment is also an option, such as adaptive antenna arrays (Controlled Radiation Pattern Antennas) that are effective against broadband jammers and operate by blocking all signal reception in areas in which it has detected interfering signals. This may result in satellite availability issues, since the antenna blocks all sources coming from the affected sector.

Shipboard use of satellite navigation multi-element arrays has not been widely reported, but the cost of such equipment can be estimated at around £10k [26].

Other proposed techniques, such as Polarisation Discrimination use a detection and tracking/control channel to identify and track the interfering signal and a hybrid junction to null the interference component of the signal, costing around £150 [26].

It is important to recognise, however, that those equipment may reduce the likelihood of a successful jamming but will not eliminate the threat. Therefore, some sort of backup system will be needed and the options will be discussed further in this chapter.

e) Spoofing and Meaconing

Spoofing is a technique that aims to cause a receiver to lock onto legitimate-appearing signals and slowly deviate it from the desired path. It is more difficult to achieve than jamming, but can be much more effective and can defeat nearly all anti-jamming techniques.

Meaconing has a similar effect but consists in the reception, delay and rebroadcast of navigation signals.

Edwin L. Key [28] states that the best anti-spoofing technique is probably the use of a multiple-element antenna to measure the angle of arrival of all received signals and since it is very unlikely that a spoofer can match the angle of arrival of the navigation satellites, their signals are easily rejected.

The problem is that no anti-spoofing equipment is commercially available up to the present day.

f) Service Shutdown

An attack against the control components of the satellite navigation systems and even, however more unlikely, against the satellites themselves must also be considered, as well as accidents that could disrupt the navigation services provided.

The introduction of the GALILEO system and the combined use of GPS and GLONASS, each of them controlled by different organisations, will drastically reduce the risk of a complete satellite navigation shutdown.

4.2.3 Proposed Position Fixing System

For the reasons discussed in the previous sections, a standalone satellite navigation system, even considering the combined use of GPS, GLONASS and GALILEO, would not provide a solution robust enough to cope with the variety of external "threats" to its integrity, completely substituting the human element.

Satellite navigation will still be the main component of the navigation system of the unmanned ship, but different and independent means to establish a position will be needed in order to cover the weaknesses of that system.

Those extra components will be discussed in the following paragraphs in the context of the different navigation phases, as previously defined.

4.2.3.1 Ocean and Coastal Phases

Loran-C seems to be the only system capable of providing a backup in the event of satellite navigation outages, providing accuracies of about 0.1 – 0.25 nm, although only over a limited part of the globe, as seen in Figure 25.

Loran-C is ground based and operates in the 90 – 110 kHz band, very far from the frequencies allocated to navigation satellites, which means that virtually any interference to GPS, GLONASS or GALILEO signals will have no effect on Loran-C.

Moreover, Loran-C system has radiated power levels ranging from 0.325 to 1.6 MW, against the very low power levels in which satellite navigation systems operate, making it extremely difficult to jam [26].

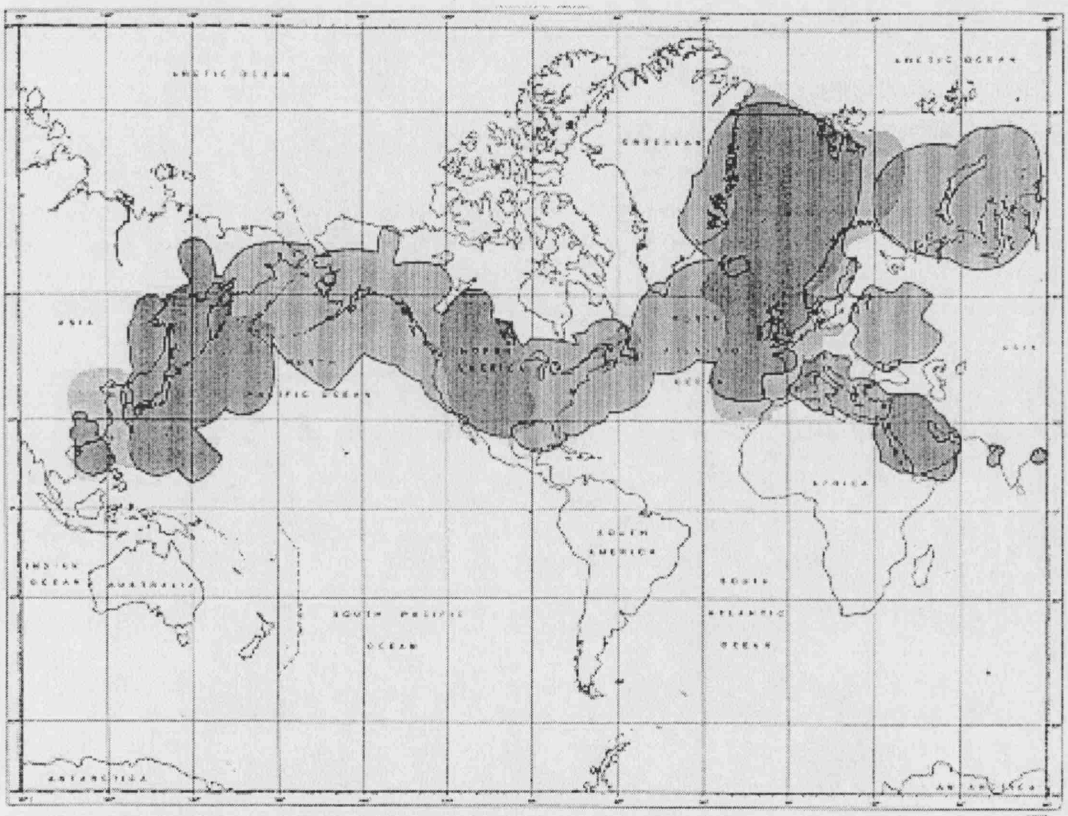


Figure 25 – Loran-C Coverage [29]

Since no other electronic navigation system can currently compete with Loran-C as a backup to satellite navigation systems, a serious constraint is applied to the design of an unmanned ship, limiting the routes to areas under Loran-C coverage, as shown in Figure 25.

4.2.3.2 Harbour Approach

Two alternatives will be discussed in this section, one of them based on a ship-based autonomous operation and the other highly dependent of ground base components.

The first proposal is based on the combination of high accuracy of satellite navigation systems with the recognised high repeatability of Loran-C (18 to 90 meters) that could enhance Loran's absolute accuracy to the required levels for this navigation phase.

Figure 26 shows GPS with SA on and Loran-C data taken over the same 24-hour period, and graphically demonstrates the assertive in the previous paragraph.

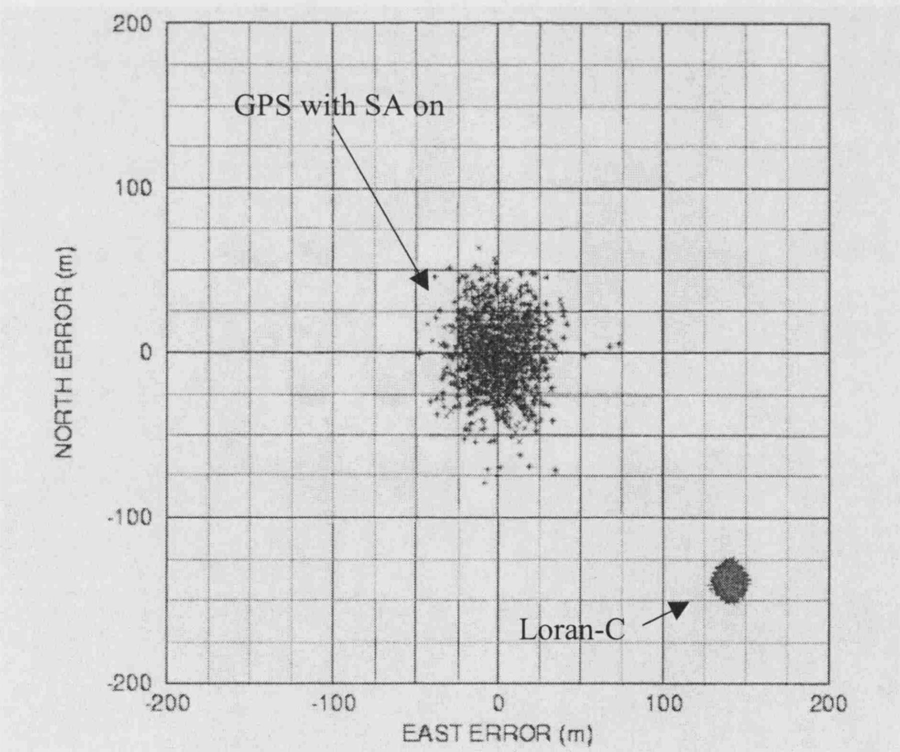


Figure 26 – GPS and Loran-C Scatterplots (24 hour sample) [30]

As a terrestrial system, Loran's ground waves are affected by the earth's conductivity over the ground wave propagation path, resulting in an inherent bias that compromises Loran's absolute accuracy.

Small variations in the velocity of propagation between that over seawater and over different landmasses are known as the Additional Secondary Factor (ASF). Fortunately, ASF vary very little with time and tables are often used to correct for this accuracy bias.

Since satellite navigation systems are not subject to these same influences, they can be used to calibrate Loran's absolute accuracy. One method would be to use differential positioning systems (e.g. DGPS) for calibration and to generate a local table of Loran ASF corrections, which could be stored in a receiver's memory and accessed as required.

A program to generate ASF correction tables is currently underway in Europe, but regardless of the method implemented, satellite navigation capabilities can be used to remove Loran's positional bias due to variations in the earth's conductivity. GPS/GLONASS/GALILEO calibrated Loran would therefore enable Loran to operate with an absolute accuracy comparable to those obtained with satellite navigation systems, and most importantly, to function as a highly accurate, independent radio navigation system in situations where satellite navigation is unavailable [30].

Since the this solution will depend on the availability of ASF corrections for the desired areas of operation, another proposal will be presented, based on the use of Vessel Traffic Systems (VTS) capabilities, which are already available in a number of major ports.

Those services usually employ a number of sensors, such as radar, radio direction finders, video and infrared cameras, together with information transmitted by ships operating in its jurisdictional area, in order to monitor and facilitate the safe and efficient transit of vessel traffic to prevent collision, ramming, grounding, and the losses (lives and property) and environmental damage associated with these accidents.

These systems can track vessels using radar with a position accuracy varying from less than 20 meters for a radar-to-target distance of 3nm to less than 100 meters for a distance of 24 nm and can provide position update intervals of less than 3 seconds [31].

The positions of the ships determined by the VTS after satellite navigation outages could then be transmitted to all the vessels in the area by some kind of data link, for instance by means of an Automatic Identification System (AIS) transponder, that will be discussed later in this chapter in the section dedicated to collision avoidance.

4.3 Collision Avoidance

In order to establish the action to be taken by the unmanned ship to avoid collision at sea, bearing and distance from other ships in the vicinity, as well as relative speed and relative course of those vessels must be available at all times.

Ideally, the points where those vessels intend to change course or speed are also important to define the optimum response of a ship, based on the IMO Convention on the International Regulations for Preventing Collisions at Sea (COLREG).

The Automatic Radar Plotting Aid (ARPA) and the Automatic Identification System (AIS) will be discussed, as they will form the heart of the unmanned ship's collision avoidance system.

4.3.1 Automatic Radar Plotting Aid (ARPA)

The IMO International Convention for the Safety of Life at Sea (SOLAS) established that ships of 10,000 gross tonnage and upwards, constructed on or after 1 September 1984, must be fitted with an Automatic Radar Plotting Aid (ARPA).

This equipment has the ability to automatically track a number of targets – usually around 20 – and calculate their CPA and TCPA and is capable of simulating the effect on all tracked targets of an own ship manoeuvre without interrupting the updating of target information.

Being in use for a long time, the weaknesses of the system are well known, such as targets wandering away and fusing with the shore, especially in narrow channels. This equipment by itself is not reliable enough to be the sole component of a collision avoidance system, but can provide important information, sometimes unavailable by other means.

4.3.2 Automatic Identification System (AIS)

The AIS is a shipboard broadcast transponder system, which operates in the VHF band, capable of automatically sending ship information, without involvement of ship's personnel, such as identification, position, heading, length, beam, type, draught, and other safety-related information, to other ships as well as to shore based stations. It is capable of handling well over 2,000 reports per minute and updates as often as every two seconds [39].

Each AIS system consists of one VHF transmitter, two VHF Time Division Multiple Access (TDMA) receivers, one VHF DSC receiver, and a standard marine electronic communications link to shipboard display and sensor systems.

Although only one radio channel is necessary, each station transmits and receives over two radio channels to avoid interference problems, and to allow channels to be shifted without communications loss from other ships.

Position and timing information is normally derived from a global navigation satellite system receiver (e.g. GPS), including a differential receiver (e.g. DGPS) for precise position in coastal and harbour waters.

It is expected that the relative position of ships in the same area will be more precise than the absolute position given by satellite navigation systems, since most of the error sources, as discussed in section 4.2.2.1, will produce equal effects in their position determination.

Other information obtained from shipboard equipment through standard marine data connections will also be broadcasted by AIS equipment, as required by IMO [40]:

a) Static:

- IMO number (where available)
- Call sign & name
- Length and beam
- Type of ship
- Location of position-fixing antenna on the ship (aft of bow and port or starboard of centreline)

b) Dynamic:

- Ship's position with accuracy indication and integrity status
- Time in UTC
- Course over ground
- Speed over ground
- Heading
- Navigational status (e.g. NUC, at anchor, etc. - manual input)
- Rate of turn (where available)
- Optional - Angle of heel (where available)
- Optional - Pitch and roll (where available)

c) Voyage related:

- Ship's draught
- Hazardous cargo (type)
- Destination and ETA (at masters discretion)
- Optional - Route plan (waypoints)

Static and Voyage related information will be updated every six minutes, while dynamic information update rate will depend on speed and course alteration according to Table 7.

Situation	Reporting interval
Ship at anchor	3 min
Ship 0-14 knots	12 sec
Ship 0-14 knots and changing course	4 sec
Ship 14-23 knots	6 sec
Ship 14-23 knots and changing course	2 sec
Ship > 23 knots	3 sec
Ship > 23 knots and changing course	2 sec

Table 7 – AIS Reporting Interval

The effective range will depend on antenna heights, similar to VHF communications and radar horizons but, in most cases, at least a twenty-mile range can be expected.

The 73rd Session of the IMO Maritime Safety Committee decided that all ships engaged on international voyages of 300 gross tonnage and upwards, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships irrespective of size shall be fitted with AIS, as follows [4]:

- Ships constructed on or after 1 July 2002;
- Ships engaged on international voyages constructed before 1 July 2002:
    - In the case of passenger ships, not later than 1 July 2003;
    - In the case of tankers, not later than the first "safety equipment survey" after 1 July 2003;
    - In the case of ships, other than passenger ships and tankers, of 50,000 gross tonnage and upwards, not later than 1 July 2004;

- In the case of ships, other than passenger ships and tankers, of 10,000 gross tonnage and upwards but less than 50,000 gross tonnage, not later than 1 July 2005;
- In the case of ships, other than passenger ships and tankers, of 3,000 gross tonnage and upwards but less than 10,000 gross tonnage, not later than 1 July 2006;
- In the case of ships, other than passenger ships and tankers, of 300 gross tonnage and upwards but less than 3,000 gross tonnage, not later than 1 July 2007; and
- In the case of ships not engaged on international voyages, not later than 1 July 2008.

The implementation of this equipment will provide all information needed for making collision avoidance decisions, but will be restricted to the AIS equipped ships.

At a currently estimated cost of £5k [38], it is very unlikely that recreation, small boats and other ships not covered by the IMO resolution will voluntarily be fitted with such equipment, especially because they would not fully benefit from it [43].

For this reason and to fulfil the role of a backup system for he AIS, the use of ARPA as a complementary system will be required.

Integration issues of ARPA and AIS will then have to be considered, since most of the time, due to their different principles, both systems will be providing slightly different data for the same target.

As an example, Figure 27 reproduces the replay of "Regal Princess" ECDIS while an AIS performance test was being carried out in British Columbia and South Alaska in September 2000 [41]. Different information provided by AIS and ARPA can be clearly seen both graphically and numerically.

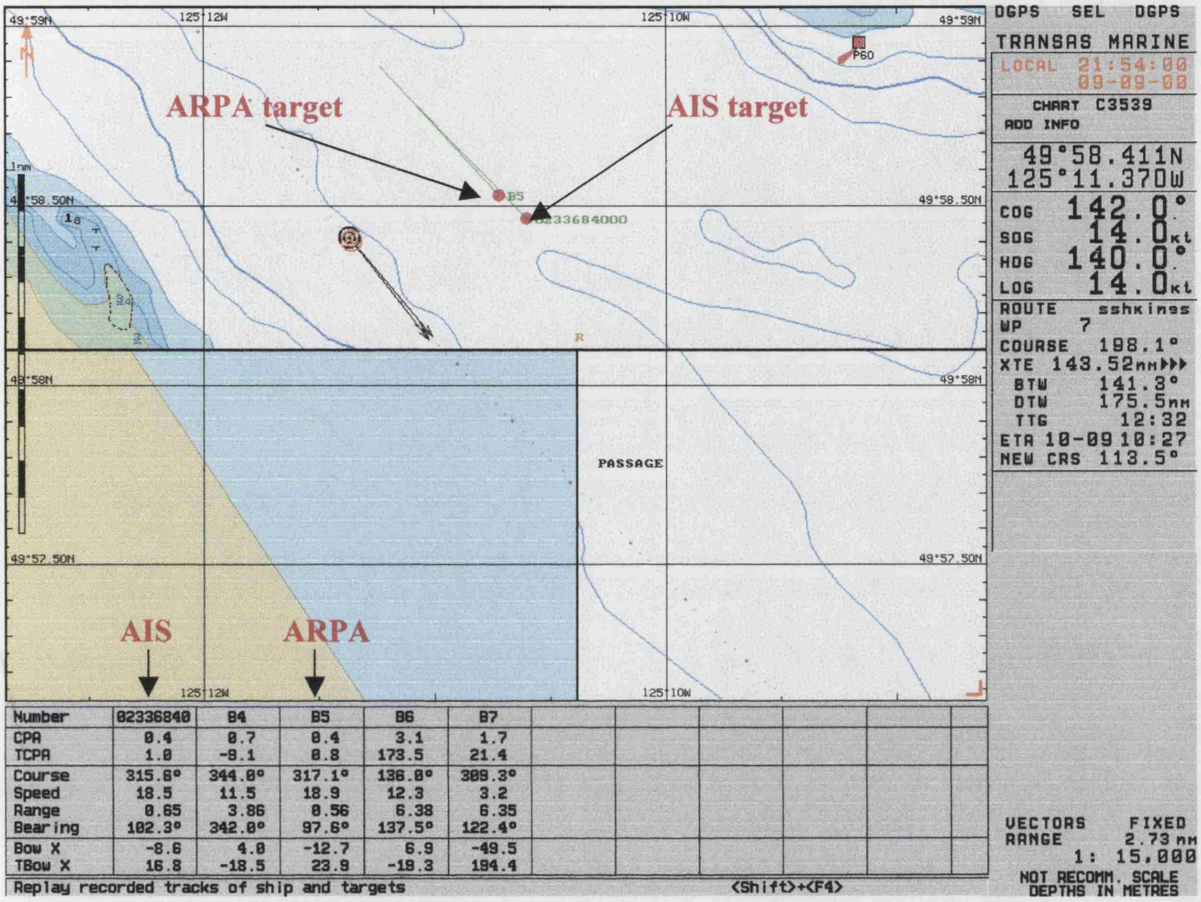


Figure 27 – ARPA versus AIS [42]

The discussion of the integration issues is outside the scope of this work and more information can be found in the Universal Automatic Identification System website [42]. It is clear, however, that these issues will have to be solved before the full implementation of the system.

4.3.3 Vessel Traffic Services (VTS)

As already mentioned in section 4.2.3.2, Vessel Traffic Services usually employ a number of sensors, such as radar, radio direction finders, video and infrared cameras, together with information transmitted by ships operating in its jurisdictional area.

The role of this service still varies from one port to another, from monitoring station to shore-based pilotage provider. Recently, there have been discussions regarding the adoption of an approach similar to the one performed by Air Traffic Controllers, where a VTS would effectively control the traffic within its jurisdiction [47][48].

A number of issues, such as VTS responsibility in case of an accident, reduction of Master's authority and especially deep roots of old traditions, are challenging the adoption of this new ship–shore relationship [47], so well proven in the aviation industry.

It is quite unbelievable that the simple comparison between the number of collisions at sea and in the air hasn't convinced all parties involved in the shipping industry that the old tradition of the "freedom of the seas", which implies that ships have the right to operate everywhere they wish, has no place in the present safety standards expected from the maritime industry.

It the future, it is expected that a VTS will perform a positive traffic control in its jurisdictional area, which would make the design of an unmanned ship much easier, as far as collision avoidance in restricted waters is concerned.

In this work, however, only the VTS ability to track the vessels operating in its jurisdictional waters, by means of radar, AIS, video and infrared cameras will be considered.

By transmitting to the unmanned ship, via an AIS-like transponder, all the targets acquired by the VTS system, a third source of collision avoidance related data could be integrated to the system.

Since land based radars have potentially better resolution and accuracies than ship-mounted counterparts, allied to the use of alternative sensors such as optical or infrared, the probability of detecting small boats would be increased.

4.3.4 Routeing Systems

A number of options were presented in the previous sections in order to deal with the issue of collision avoidance with small boats not fitted with an AIS transponder, but it is clear that the performance of any unmanned system using currently available technologies cannot be considered fully satisfactory.

A solution for this problem may lie in the adoption of measures similar to those already used to allow the operation of large vessels constrained by their draft in certain areas, where dedicated fairways were established and small vessels must keep the passage clear.

Regulation 8, Chapter V of SOLAS convention determines that any contracting government may propose a ship's routeing system in order to contribute to the safety of life at sea, safety and efficiency of navigation and/or protection of the marine environment.

The convention also stipulates that ships' routeing systems may be made mandatory for all ships, certain categories of ships or ships carrying certain cargoes, when adopted and implemented in accordance with the guidelines and criteria developed by the IMO.

Based on this regulation, governments interested in the operation of unmanned ships could define fairways that must be adhered to by such vessels throughout their voyage.

On the other hand, rule 9 b) of COLREG specify that a vessel of less than 20 meters in length or a sailing vessel shall not impede the passage of a vessel which can safely navigate only within a narrow channel or fairway.

The adoption of a routeing system allied to the other collision avoidance systems discussed in the previous sections of this chapter can bring the risk of collision with small boats or other vessels not required to be fitted with AIS within acceptable levels.

It is important to note that the adoption of the proposed solution would only interfere with the operation of small boats and sailing vessels, since the unmanned ship would have no precedence over any other type of vessel as far as collision avoidance is concerned.

4.4 Route Planning

Many shipping companies have already established "company approved" routes from berth to berth, such as the one shown in Figure 28, in order to increase safety and to ensure compliance with regulations, as well as to achieve improved efficiency and time saving on board their ships.

Shell UK, as an example, has a database of more than 2000 waypoints covering its trading areas and, although Masters are entitled to deviate from the route should they consider it necessary, reasons for such deviation would have to be given, and Head Office informed [44].

Shell UK Ltd
Coastal Operations Department

Passage Plan Report

FROM : Fawley
TO : Jersey

Vessel : *Achatina*
Estimated speed : 12.0 knots
Passage distance : 145 nm
Passage time : 000:12:07
Route name : Fawley - Jersey 21
Passage plan name : Untitled

Options : Tides [Off] Variation [Off] Deviation [Off]
Calculated : 16:17:23 15/03/1999
Viewed : 16:17:38 15/03/1999

Memo
Ensure report to Joburg Traffic. Via south of Ryde, middle and east entrance to Solent

Rte Wpt No	Datum	Time	Elap Time (ddd:hh:mm)	Name	Position	Crse (°T)	Leg (nm)	Accum (nm)	To Go (nm)
1	WGS84	16:00:00 12/04/1999	000:00:00	OFF FAWLEY JETTY	50°50.15'N 001°19.28'W	142	0.91	0.00	145
2	WGS84	16:04:33 12/04/1999	000:00:05	HOOK BUOY OUT	50°49.43'N 001°18.40'W	139	0.42	0.91	144

Memo (waypoint 1)
HAMBLE POINT BUOY BRG 090 X 4 CABLES

Memo (waypoint 2)
REPORTING POINT

HOOK BUOY BRG 036 X APPROX 1.3 CABLES

Figure 28 – Company Approved Passage Planning [44]

A procedure similar to this one could be adopted in the unmanned ship, where passage plans are developed and updated by shore personnel and transferred to the ship's navigation control system.

The only reasons to deviate from these pre-defined routes would be collision avoidance, weather conditions and navigational warnings.

In order to make collision avoidance manoeuvres possible, in the same way that "company approved" passage plans are made, safe paths with variable widths should be established around the waypoints, where the ship will be allowed to navigate. Those widths will depend on the navigation phase, on the particular characteristics of the waters in which the ship is sailing and on the manoeuvring characteristics of the vessel, but can still be pre-defined by shore personnel.

The maximum speed and the minimum distance from other ships must also be defined for each navigation phase.

As far as navigational warnings are concerned, Notice to Mariners are available online for major ports and can be accessed by shore personnel responsible for updating the route planning, and new waypoints can be generated and sent to the ship.

4.5 Weather Routing

Regarding weather conditions, a number of companies [45][46] already provide 24-hour weather routing services, which usually includes initial weather conditions and routing recommendation, continuous en route weather forecast, diversion recommendation and fine-tuning of the recommended route.

As a backup for the weather routing services, roll and pitch sensors should also be fitted in the unmanned ship, in order that excessive motion and stresses can be avoided when particularly dangerous sea conditions are met, such as when the wavelength is in the order of 1 to 1.5 times the length of the ship.

In these cases, this data will have to be transmitted to shore, where a new route will be defined, in consultancy with the weather routing service provider, and sent to the ship.

The routeing system required for the collision avoidance with small boats and sailing vessels described in section 4.3.4 will, however, pose a significant limitation regarding route changes during a voyage.

Unless it is possible to define multiple routeing systems between two ports with connecting lanes in suitable intervals, which is very unlikely, the length of the legs of the intended voyage will have to be limited in order to permit a reliable weather forecast for the duration of each trip.

4.6 The Unmanned Ship Navigation System

Having described the navigation requirements of the unmanned ship, as well as the equipment needed to fulfil those requirements, it is time to see how they need to integrate in order to provide a navigation system as reliable and effective as those on board conventional vessels.

The use of a combined GPS/GLONASS/GALILEO receiver capable of processing differential corrections, when available, together with an ASF-corrected LORAN-C receiver would form a sufficiently redundant navigation system for the unmanned ship, capable of continuously providing the position accuracies required for the ocean, coastal and harbour approach phases, with high update rates, within the areas limited by LORAN-C coverage.

If ASF tables are not available and GNSS backup is performed by VTS radar tracking, as described in section 4.2.3.2, the required accuracy and fix interval would still be met.

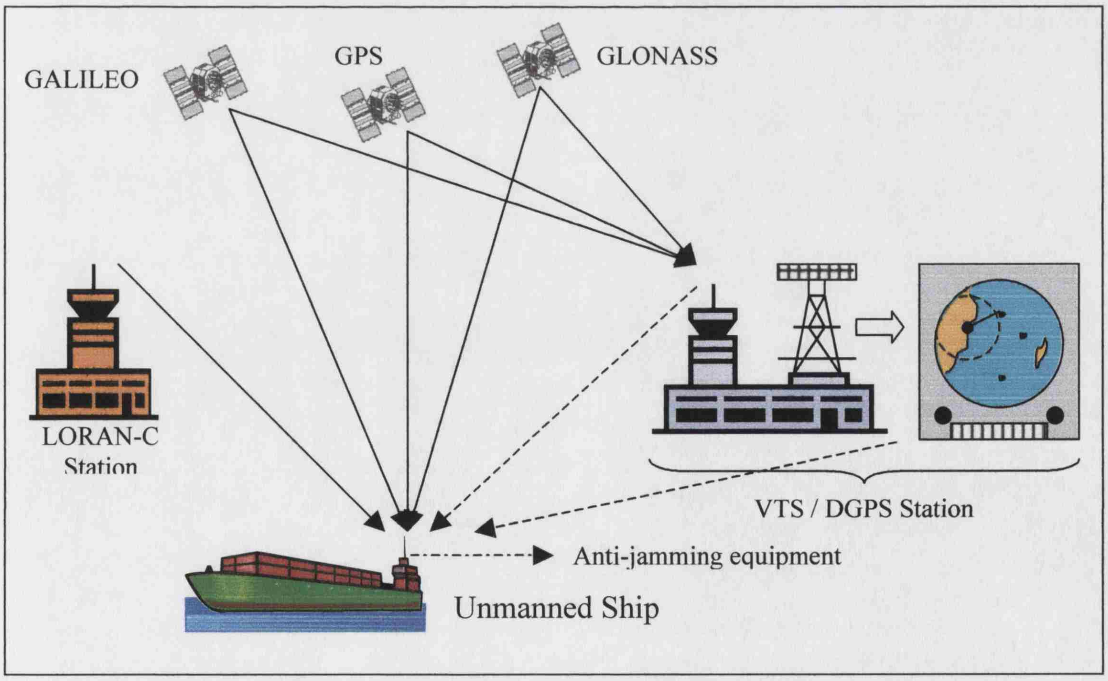


Figure 29 – The Position Fixing System

The components of the unmanned ship position fixing system can be seen in Figure 29 and the expected performance is summarised in Table 8.

Phase	Required Accuracy	Available Accuracy	Required Fix Interval	Available Fix Interval
Ocean	1 – 2 nm	4 m – 0.25* nm	15 min – 2 h	<1 sec
Coastal	0.25 nm	1 – 0.25* m	1 min	<1 – 3** sec
Harbour Approach	5 – 20 m	1 – 20*** m	5 – 10 sec	<1 – 3** sec

* LORAN-C accuracy
** VTS radar update rate
*** LORAN-C repeatability / VTS radar accuracy

Table 8 – Expected Position Fixing Performance

Considering that a routeing system is adopted, the integration of AIS, ARPA and VTS data will provide the basis of the collision avoidance system of the unmanned ship, since they will provide all information needed to evaluate the relative motion between the unmanned ship and other vessels in the vicinity.

The results of this calculation, together with the latitude and longitude given by the position fixing system and the speed and course, both over the ground and over the sea, will allow the system to calculate a new waypoint and/or a new speed in order to avoid any possible collision or close quarter situation, based on COLREG rules and within the limits established by the pre-defined safe path determined in the passage planning process, as discussed in section 4.4.

This new waypoint and the new speed will be included in the route planning, as an update to the previous route, and the process can start all over again for this new situation.

This is exactly the procedure followed by a conventional navigation watch, with the potential advantage offered by the greater number of variables that the system can consider and at a much greater update rate, which could lead to less manoeuvres and to a safer system.

The complete navigation system proposed to the unmanned ship can be seen in Figure 30, where the integration of the subsystems described in the previous sections can be better visualised.

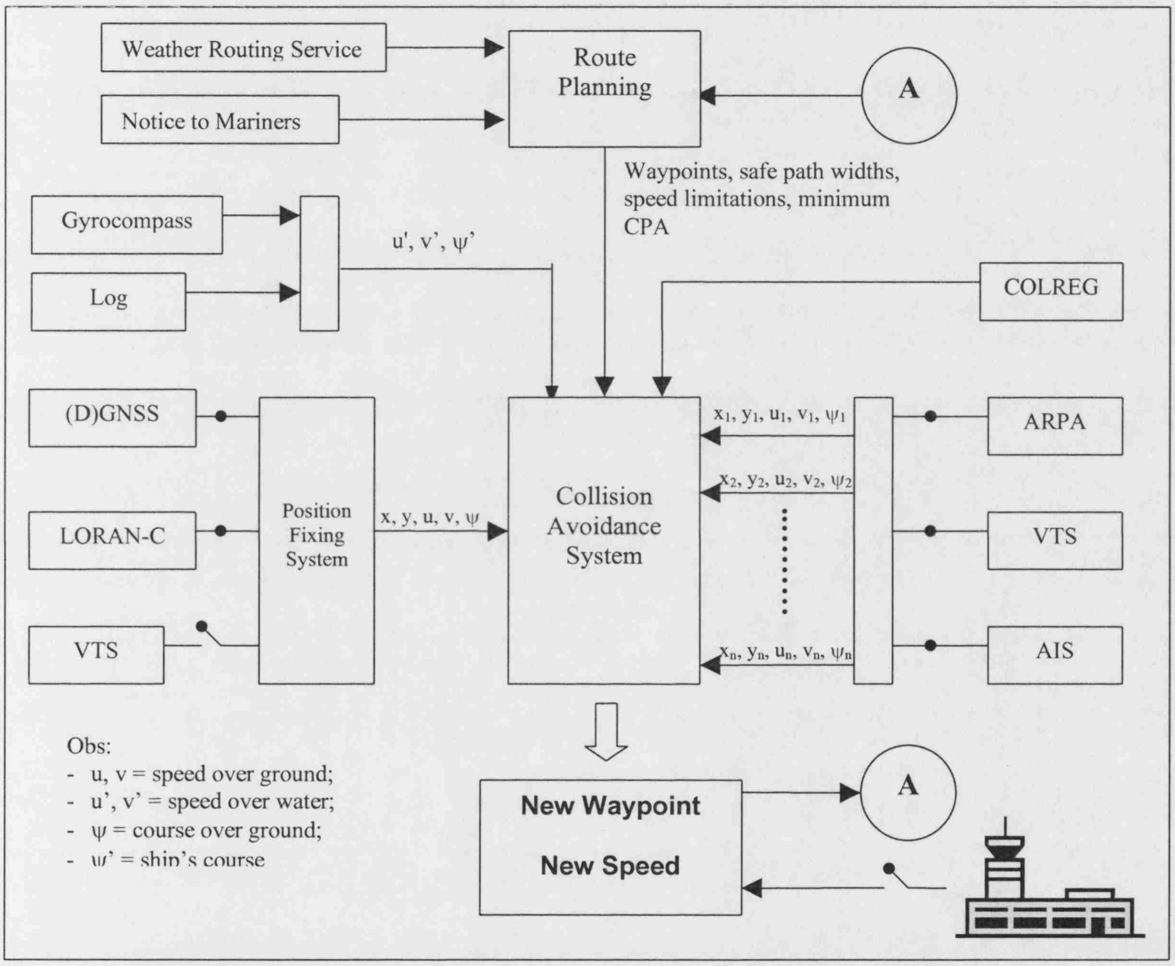


Figure 30 – Unmanned Ship Navigation System

The system described so far would be capable of taking the ship up to the position where docking operations could initiate.

4.7 Summary

In this chapter, the requirements for an unmanned navigation system were defined and, after a survey of the available related technologies, a complete system was proposed and the following conclusions can be drawn:

- The combined use of satellite navigation systems (GPS, GLONASS, GALILEO, etc) and their correspondent differential systems can provide a position fixing solution accurate enough to fulfil the requirements of ocean, coastal and harbour approach phases of marine navigation, without the need of human intervention on board;

- There are several technologies available to reduce the effects of potential intentional and unintentional disruption to satellite navigation systems, but the threat cannot be fully eliminated;

- Hyperbolic ground based navigation systems (i.e. Loran-C) used with Additional Secondary Factor (ASF) correction tables, when necessary, have the required characteristics to provide a backup in the event of satellite navigation outages, but limit the areas where an unmanned ship could operate to those covered by this service;

- Vessel Traffic Systems (VTS) can track the unmanned ship and provide remote pilotage services, being an extra source of position fixing;

- Automatic Identification System (AIS) has all the characteristics needed to provide the basis of an unmanned collision avoidance system, but will not be fitted on board ships under 300 GT;

- Automatic Radar Plotting Aid (ARPA) and the broadcast of targets acquired by VTS in its jurisdictional area must be used to increase the probability of detection of small vessels not fitted with an AIS;

- The most effective way to minimise the risk of collision with small boats not fitted with an AIS is the adoption of routeing systems for the unmanned ships in accordance with SOLAS and making use of rule 9 of COLREG in the pre-defined fairways to keep small boats and sailing vessels from impeding the safe passage of the unmanned ships;

- The use of company approved passage plans and weather routing services complete the proposed unmanned navigation system.

CHAPTER 5

BERTHING AND MOORING

5.1 Introduction

In the previous Chapter, a complete navigation system capable of taking the ship from one port to another was described. The system, however, do not cover the initial and the final phases of navigation when the ship will have to be directed to and from the wharf.

The Berthing phase is when the ship is brought up within a range of around 300 meters from the berthing line and is then moved alongside, tug assisted or autonomously, approximately parallel to the berthing line until contact is made with the fenders.

In this phase, collision avoidance is not an issue anymore, since it is expected that traffic management at the port would not allow vessels to interfere during this manoeuvre.

On the other hand, a real time precise determination of the position of both the bow and the stern of the vessel in relation to the fenders is essential in order to control the stresses of berthing impact. In this case, centimetre-level accuracy is needed with updates every second, at least.

Apart from that, suitable alternatives to the current mooring practices will have to be studied, since it is probably the most labour intensive task on board a ship.

In this Chapter a berthing and mooring system for the unmanned ship will be proposed, together with an overview of the main technologies available.

5.2 Sub-meter Accuracy Positioning Systems

Controlling a ship at the berthing stage requires precise and real-time determination of not only the vessel position, but also the heading and yaw rate.

A number of currently available technologies are discussed in the following paragraphs and their suitability for the desired task is assessed.

5.2.1 Real Time Kinematic GPS

Relatively recently, a new positioning technique has been developed, the Real Time Kinematic Systems (RTK GPS) that employs a method of carrier-phase differential GPS positioning, allowing users to obtain centimetre-level position accuracies in real time.

The discussion of the whole theory behind RTK GPS is outside the scope of this work, but a brief description of the principles involved will be presented in the following paragraphs.

Similar to differential techniques described in Chapter 4, RTK systems also requires a base station at a fixed known position less than 10 km from the receiver, but comes at a cost in terms of overall system complexity because the measurements are *ambiguous*, requiring the incorporation of an "ambiguity resolution" (AR) algorithm within the data processing software [21].

GPS receivers determines the travel time of a signal from a satellite by comparing the "pseudo random code" it is generating, with an identical code in the signal from the satellite.

The receiver slides its code in time until it synchronises with the satellite's code. The amount it has to slide the code will then be equal to the signal's travel time.

The problem is that even with both signals slightly out of phase, they can still logically match, as can be seen in Figure 31, where the satellite signal is non-zero while the receiver signal is also non-zero.

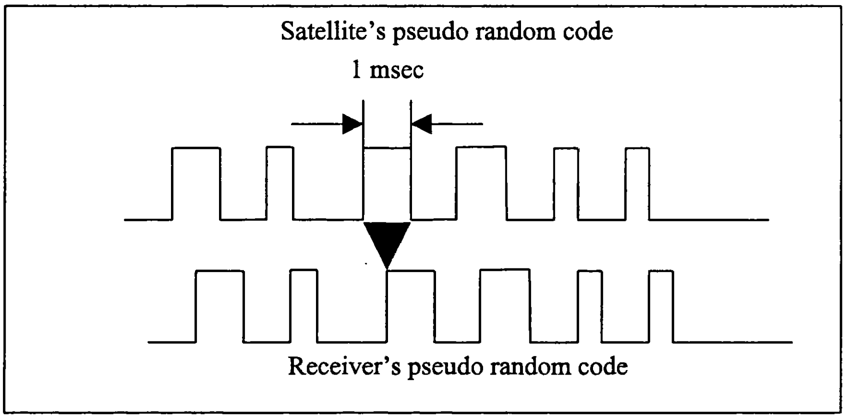


Figure 31 – Pseudo Random Code Matching

The pseudo random code has a bit rate of approximately 1 MHz, which at the speed of light will represent a length of around 300 meters. However, receiver designers have come up with ways to make sure that the signals are almost perfectly in phase. Good machines get with in a percent or two, still representing at least 3-6 meters of error.

If the carrier wave is used, with a frequency in the order of 1.57 GHz, the wavelength is reduced to around 20 centimetres and if the same performance of one percent of perfect phase is achieved, an accuracy of 3 to 4 millimetres will be theoretically possible.

Since the carrier is so uniform, it is very difficult to determine which part of the signal has to be used. However, if the code measurement can be made accurate to say, a few meters as achieved with DGPS, we only have a few wavelengths of carrier to consider as we try to determine which cycle really marks the edge of our timing pulse.

Resolving this "carrier phase ambiguity", as it is called, for just a few cycles is a much more tractable problem and is the basis of the RTK systems.

Although RTK systems represent the state-of-the-art in GPS COTS[13] technology, there are several conditions (or constraints) that must be fulfilled.

If satellite signals were continuously tracked and loss-of-signal-lock never occurred, the integer ambiguities once determined would be valid for the whole period that the satellite was being used.

However, satellite signals can be shaded (for example, when the receiver passes under a bridge), in which case the ambiguity values are lost and must be re-determined. This process can take from several tens of seconds up to a few minutes with present GPS COTS systems [22] [23].

During this "re-initialisation" period, centimetre accuracy positioning is not possible and there is a dead time until sufficient data has been collected to resolve the ambiguities.

This technology, alone, would not be sufficient for berthing / unberthing operations where a loss of accurate position, even for some seconds, is unacceptable.

It must be noted, though, that this is a very recent technology and the so-called "on-the-fly ambiguity resolution techniques are becoming faster and more reliable.

[13] Commercial Off-the-Shelf

The European GALILEO system, already discussed in the previous chapter, also promises three frequencies that would make the concept of Three Carrier Ambiguity Resolution (TCAR) possible.

The key to TCAR lies in measuring the phase of the signals at different frequencies and combining them to form so-called 'wide-lane frequencies'. The integer ambiguity in the number of carrier cycles of each 'wide lane' can be resolved provided the noise at each step is small enough compared to the wavelength of that particular wide-lane combination. The final result is a range obtained with the accuracy of the carrier, typically at millimetre level, almost instantly.

In any case, the need for a backup system exists and additional equipment will be discussed in the following sections.

5.2.2 Laser Docking Systems

Laser systems, used primarily in the offshore industry for repetitive, high accuracy positioning and tracking of marine vessels, and static and semi-static anchored structures, are strong candidates to provide centimetre accuracy positioning information.

This measurement system is already used as a docking aid of large tankers in a number of terminals and some manufacturers claim that statistical studies show that terminals without laser docking systems have an accident one in every 1000 berthing operations compared to one in every 10,000 berthing operations at terminals with laser systems [33].

These systems, (see Figure 32) usually have two sensors measuring the distances of bow and stern sections from the fenders using laser units installed on the proper position of a berth. This data is then transmitted via radio link to the ship, where speeds of approach and the angle of the ship to the berthing line will be derived from the distance measurements.

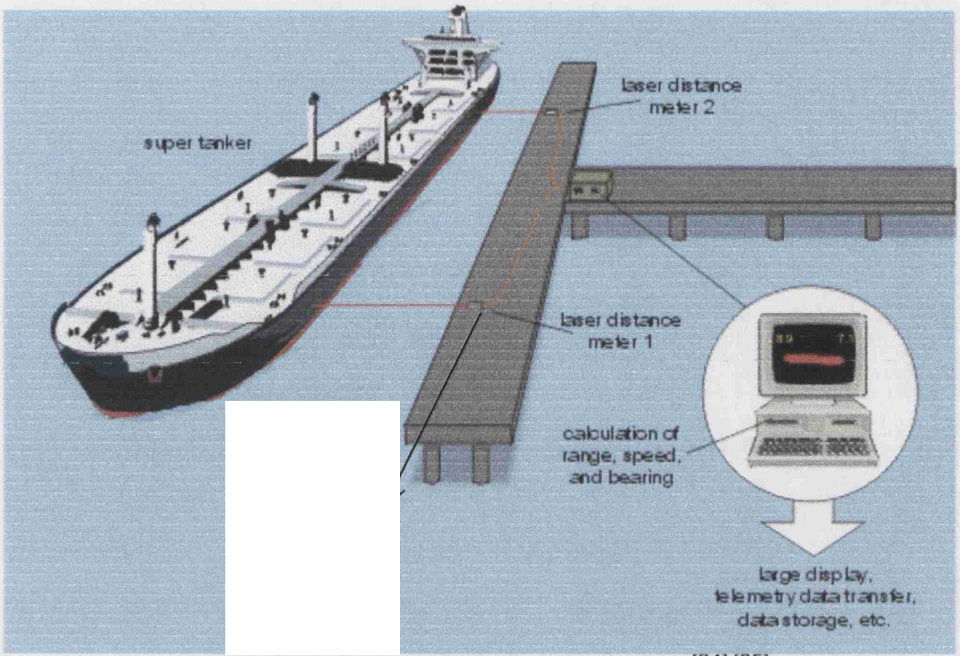


Figure 32 – Laser Docking System [34] [35]

This system however, would only provide distances in one axis, perpendicular to the quay and movements parallel to the berthing line would not be monitored.

Unless very specific geographical conditions are met, making it possible to place other laser distance meters to monitor the ship movements parallel to the quay, this system would not be suitable as a backup for the RTK satellite system.

5.2.3 Inertial Navigation

The use of an inertial navigation system (INS) was also investigated [36] [37], but since even very sophisticated inertial sensors found on board submarines drift without limit over time at a rate of around 1 nm per 24 hours [50], it would only be useful for satellite outages of a few seconds, which, especially when considering the cost of several tens of thousand of pounds, would not justify its use.

5.2.4 Approach Azimuth Guidance

A solution based on the Instrument Landing Systems (ILS) widely used in commercial aviation was also considered

In addition to the high investment needed to implement the system ashore and the requirement of an open path for the signal, which would be very difficult to obtain in a port, the width of the navigation beam varies from 3° to 6° and would not provide the required accuracy in this phase of navigation.

5.3 Proposed Berthing System

Ueno [32] proposed and successfully tested in 1997 a GPS-based positioning and attitude system, which could become the heart of an automatic berthing system.

The system was based on four RTK GPS receivers with antenna separation of 1.4 m installed on board a 35 m ship and a GPS reference station, set up at about 0.5 km from the manoeuvring area

The ship made turns off the quay and returned to the wharf, simulating the berthing operation and the data obtained by the system was compared with data from a standard station with an automatic tracking function with a precision of ±5mm.

The following results were obtained:

- Precision better than ±5 cm for positioning;
- Velocity better than ±1 cm/s;
- Attitude angles between ±0.1° and ±0.4°; and
- Yaw rate about ±0.2°/s

Although the test was carried out with post-processed data, since equipment with "on-the-fly" ambiguity resolution capability was unavailable at the time, it demonstrates the potential of satellite navigation systems as the principal sensor for automatic berthing.

On the other hand, a backup system providing data at least as precise as those obtained with satellites is needed, since a loss of track of the vessel at this stage could be catastrophic.

One option would be boarding the vessel when she approaches this final phase of navigation, but in this case conning positions similar to the ones found in conventional ships would have to be provided, as well as some of the "life support equipment" mentioned in Chapter 3, which could undermine some advantages of the unmanned ship.

Another solution envisaged is the provision of means to remotely control the ship at this final stage. This arrangement will need a very high bandwidth ship-shore communication link, capable of transmitting all information needed by the operator ashore, including video images.

Such a system was successfully demonstrated by QinetiQ [80], with an Abovewater Autonomous Vehicle (AAV), called "Mimir", controlled within a range of 4 Km by a 12 Mb/sec wireless link in the 1.4 GHz band, which provide the base station operator with system health and tracking information, as well as real-time images captured by a video camera installed on the vessel.

Figure 33 – Abovewater Autonomous Vehicle (AAV) from QinetiQ [81]

The vessel was designed to enable shallow water surveys of rivers, estuaries, reservoirs, harbours or littoral waters for dredging, archaeological or marine purposes, being easily reconfigured for a variety of missions.

Mimir transmits data from its onboard sensors either to a mobile command centre or direct to a third party system, via commercial telecommunications technology. The same principle was selected as the required backup in the proposed unmanned ship's berthing system, as described in the following paragraphs.

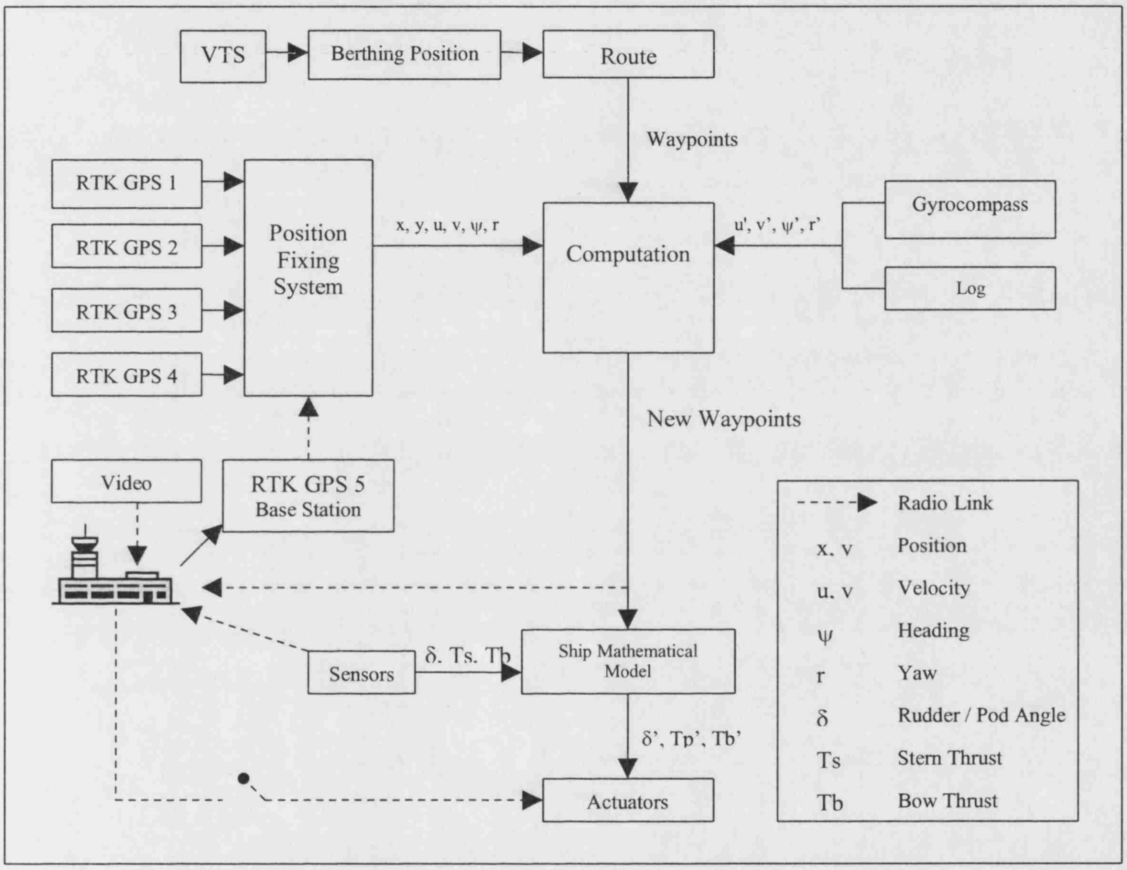


Figure 34 – Proposed Berthing System

The proposed berthing system, a combination of the system described by Ueno [32] and the remote control technology demonstrated by QinetiQ, will assume that the vessel has enough power installed aft (pods or stern thrusters) and forward (bow thrusters), enabling the ship to be moved sideways at a pre-defined heading, at assumed environmental conditions.

The system, represented in Figure 34, will basically compare position, velocity, heading and yaw rate measurements from the Real Time Kinematic GPS receivers with information received from other sensors, such as gyrocompass and log. By merging this information with the measured actuators output, such as rudder or pod angle, stern thrust and bow thrust, and based on a ship mathematical model, a new set of parameters can be generated as input to the actuators.

As a backup in case of system failure, measurements from onboard sensors are continuously transmitted ashore, as well as real time video from cameras installed in strategic points to visualise the final approach to the quay. At any time, the automatic system could be overridden and the vessel would be remotely controlled from the base station.

5.4 Advanced Mooring Systems

Until recently, there has been no reliable alternative to the use of ropes to secure vessels and ship owners and port operators have accepted the cost inefficiencies associated with labour intensive mooring lines.

In the past few years, however, a number of technologies, ship-based and shore-based, have been proposed and successfully tested, proving that the concept of an automated mooring system is possible.

In the following paragraphs, a brief description of the systems commercially available today and their main applications will be presented.

5.4.1 Shore-Based Systems

5.4.1.1 MacGregor – NorEnT Automooring Units

This equipment, with all electrical and hydraulic components, is installed at the quay with bollards on the vessel and allows one person to automatically moor the vessel within 30 seconds.

Figure 35 – MacGregor – NorEnt Automooring Units

The system is bulky, requiring a substantial area of the quay and is currently in use in northern Europe for ferries with fixed route between two ports in dedicated terminals, with several harbour stops per day.

The operation is initiated by push buttons on a panel in the wheelhouse via radio signals. The transmitter onboard the vessel gives a signal to the receiver in the machinery house on the quay and the travelling wagon is moved downwards until it reaches a pre-determined position referring to the fender line of the vessel.

The hydraulic cylinders are pushed out until the mooring hook reaches the recess on the vessel and the wagon starts again and travels until the hook is resting around the bollard on the vessel.

The cylinders are then pulled until the fender on the vessel has reached the nominal position on the quayside fender line, when the mooring cylinders stay in stand-by position, ready for pulling movements, should the vessel leave its position transverse the quayside fender line.

Since this system was designed for dedicated terminals, it could interfere with conventional mooring of other vessels, as well as loading and unloading equipment, such as cranes and gantries.

And since it was also designed for ferries with short loading and unloading times, it does not compensate for large tidal variations, as well as for movements parallel to the quayside.

For those reasons allied to the high investment required from port operators, such a system would only be selected for a very specific service with characteristics similar to the northern Europe ferries for which it was designed.

5.4.1.2 - QuaySailor

Mooring Systems Limited, a New Zealand company, has incorporated the flexibility and characteristics of traditional mooring lines in a range of automated systems. Instead of a rope, their products use vacuum pads to provide the mooring attachment.

The vacuum pads have been tested and rated under the supervision of the international classification society Det Norske Veritas (DNV) and when combined with their proprietary three-dimensional supporting apparatus, the mooring units emulate the range of movement, resilience and elasticity of a line mooring.

Mooring Systems has a range of shore-based automatic mooring systems designed to be fitted and adapted to most quay structures.

The systems are either fitted on top of the quay, on the face of the quay or attached underneath the structure and each system has two user modes: one for remote on-board control and one for activation from the shore.

Figure 36 – QuaySailor from Mooring System Limited [82]

Essential mooring load information is monitored in real time, using portable hand-held control devices. Mooring load information is derived from the measurement of vacuum efficiencies and from monitoring movement of athwartships and fore and aft system rams.

The QuaySailor, a quay face model shown in Figure 36, has the advantage of compact stowage when not in use, enabling the system to rest behind the maximum fender compression line during berthing.

When activated, the vacuum pad support frame is extended outboard and a vacuum mooring connection is established with the ship's hull in a few seconds.

The system is much more flexible regarding tidal variations and can compensate for movements parallel to the quay in addition to transversal movements and was designed to eliminate the need of mooring lines even for ships spending long periods in harbour.

Although the technology involved in the system has already been successfully tested, QuaySailor is not yet in operation and its performance could not be evaluated.

Similar to the Automooring Unit discussed in the previous section, this system could also interfere with conventional mooring lines from other vessels, but since QuaySailor does not require any equipment to be fitted on board the vessels, its use would be available to any ship using the quay.

The need of a high investment from port operators allied with the possible impact in loading and unloading equipment operation on the quay goes against the main drivers set out in the beginning of this work, since the desired solution is the one with little or no impact in port operations and facilities.

5.4.2 Ship-Based Systems

5.4.2.1 IronSailor

The IronSailor automated mooring system from Mooring Systems Limited is a ship-based product that use the same vacuum pads described in the previous section.

In this system, the mooring units are fitted internally, close to waterline, and once activated extend outboard and secure to a counterweighted quay plate that accommodates vertical displacement.

Figure 37 – IronSailor from Mooring Systems Limited [82]

IronSailor is in operation since April 1999 on board the 12,300gt Tranzrail train, lorry and passenger ferry “Aratere”, linking the North and South Islands of New Zealand.

The system installed on the “Aratere” comprises four units located in the port side casing of the 137m hull; two near the forward end, and two aft. Four bridge-activated, watertight doors protect the units, consisting of two rectangular pads fixed within a vacuum holding frame. Each pad measures 1.2m x 1m and has been tested to loads exceeding 12.5 ton under the supervision of Det NorskeVeritas.

Attachment of the vacuum pad holding frame is by way of a universal joint to a tubular housing. The latter protects a hydraulic ram that extends and retracts the vacuum pads for mooring. This ram reverts to a soft, pressurized holding pattern in the moored condition.

Relatively compact in size, each Ironsailor accommodates two units and measures 4m x 2.5m x 2.5m. Housed above the units are the control, hydraulic, vacuum and air equipment. The vacuum pads attach to flat sheets of steel located on the wharf face that use a counterweight and float arrangement to allow free vertical movement when attached.

The Ironsailor mooring system is not limited by tidal or cargo displacement. Inching rams to the rear of the internal Ironsailor ram housing cater for fore and aft movement and act similarly to spring lines. Heeling is also compensated.

During trails in the New Zealand the equipment secured a ferry in only 4 seconds after pressing a button on the bridge and has now performed thousands of automatic mooring operations without ropes, deck crew or shore-based line gangs.

This system, designed specifically for fixed route ferries, demands less investment from the port, but still requires a significant area on the quay and is better suited for ships with dedicated berths, which is the case of the "Aratere".

5.4.2.2 SeaSailor

The SeaSailor, also from Mooring Systems Limited, is a ship-based system that utilises much of the proven technology of the IronSailor described in the previous section.

The main advantage of this new system is that it only requires a static quay plate for mooring, as shown in Figure 38, minimising the impact on shore infrastructure and providing the vessel with complete operational arrival and departure autonomy.

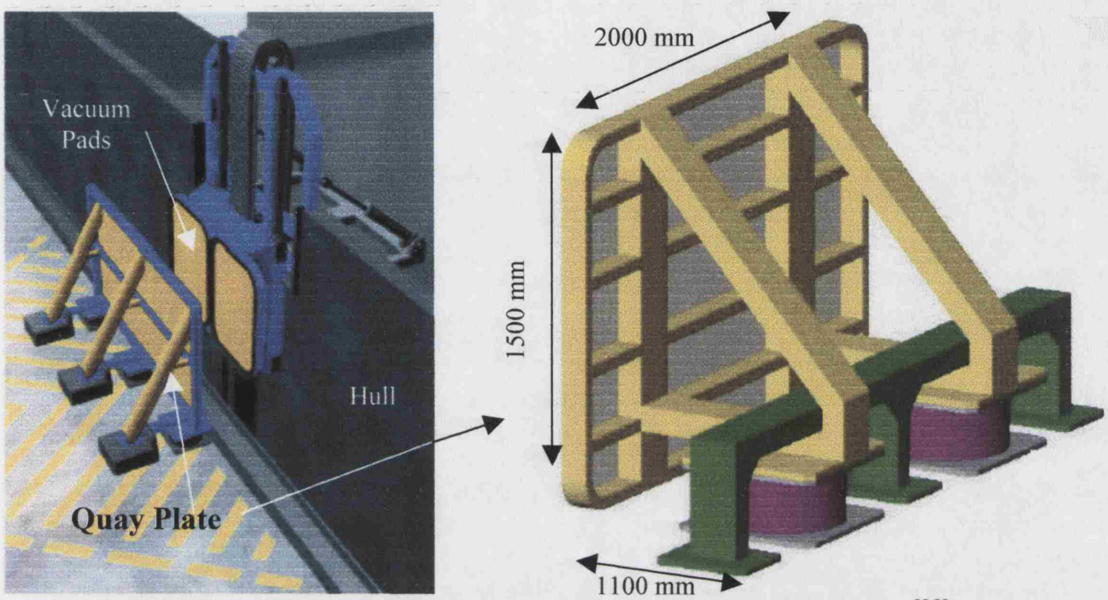


Figure 38 – SeaSailor from Mooring Systems Limited [82]

The system accommodates the variable nature of the vessel draft whilst compensating for local wind, tide and current conditions experienced in the ports of call. With the view of keeping the mooring equipment compact, the SeaSailor utilises the available freeboard of the ship to overcome the vertical ranging of the vessel at the quay.

Via a control interface it provides detailed remote real time diagnostic information on the physical mooring condition.

Apart from the vacuum pads and associated electrical, hydraulic and compressed air equipment, the ship will need to be fitted with a 'T' section rail welded to one side enabling vertical travel for each mooring unit. A method for protecting the rail from impact such as rubbing strakes will also be required.

The ‘T’ section will take athwart ships loadings induced on the mooring unit while the rubbing strake will take the fore/aft shear loadings

An example of the required arrangement is shown in Figure 39.

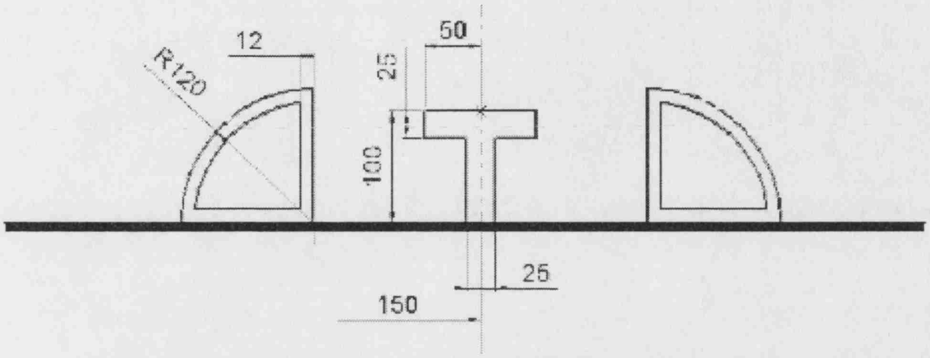


Figure 39 – “T” Section Rail and Protection

The system is designed to automatically moor a ship at the touch of a button, provided that the vessel is in a near stationary position alongside and within 450 mm of the quay.

Once the “Moor Ship” button is activated, the Vacuum Pads will be positioned to the level of the quay plates and will then extend outwards, attaching automatically to the plates.

The system will then go through a mooring sequence, securing the ship at a predetermined position ~100mm off the fender line.

After this mooring sequence is completed, which lasts approximately 6 seconds, the major components of the system will then go into sleep mode. The mooring system has limited need for power (around 2 kW) throughout the vessel’s port stay with usage dependent on maintaining vacuum levels.

In this sleep mode, the hydraulic cylinders revert to a soft pressurised holding pattern, restraining the mooring forces acting on the vessel.

When not in use and in retracted position the unit will self seal preventing water ingress into hydraulic cylinder and lever arm bay. The stowed position is at the top of the rail.

5.5 Selected Mooring System

Preference was given for the solution causing minimum impact in port infrastructure and that is flexible enough to cater for different operation profiles.

From the options described in the previous sections, the SeaSailor system from Mooring Systems Limited appears as the most suitable mooring system for the unmanned ship.

Such system will replace conventional labour intensive mooring operations, which can require up to 12 people, taking around 15 minutes to be completed.

Although the system costs around £200k for a three-port operation, including set-up, installation and commissioning, there are potential areas where efficiency can be improved and monetary savings made.

Apart from ship manning savings already discussed in Chapter 3, other factors must also be considered, such as:

- Shore Linesman Charges;
- Safety for Personnel;
- Reduced Paint Abrasion; and
- Autonomy.

Finally, following the principle that every system on board the unmanned ship must have a backup, the vessel will also be fitted with conventional bollards and mooring ropes can be passed to the quay by shore staff after the ship is secured by the automatic system.

Mooring winches, however, will not be fitted, since a slack mooring with the ropes will be desired in order to cope with tidal variations, ship movements and, mainly, not to interfere with the automatic mooring system.

5.6 Summary

In this chapter, a berthing system was proposed and a mooring system was selected for the unmanned ship.

The key points presented in this part of the thesis are:

- A position fixing system based on sub-meter accuracy "on-the-fly" Real Time Kinematic (RTK) satellite receivers can fulfil the requirements for an automatic berthing system but, similarly to the satellite navigation systems discussed in chapter 4, there are vulnerabilities that demand a backup system;

- A number of other precise positioning technologies were investigated, but none was considered adequate to perform the role of a backup for the RTK system;

- Remote control from the quay, based on video and data wireless links, was considered to be essential for the safe berthing of the unmanned ship when used in an interventionist mode, providing a backup in the event of RTK navigation outages;

- A commercial-off-the-shelf ship-based automated mooring system was selected to replace the traditionally labour intensive mooring lines

CHAPTER 6
PROPULSION

6.1 Introduction

Reliability is probably the most important aspect to be considered when applying a new concept such as the unmanned ship proposed in this thesis.

The main objective in this chapter is to design an unmanned system that would present a probability of total propulsion loss below the figures expected from a conventionally manned plant currently in operation on board merchant ships, at a minimum cost.

Maintenance issues and the limitations they impose upon an unmanned ship operation profile are also discussed.

6.2 Propulsion and Electricity Generation

Today, on board many ships, the “periodically unattended machinery spaces” concept has been successfully implemented and the technology needed to monitor and control of the propulsion and electricity generation plant from a remote location cannot be seen as risky anymore.

The main difference between this concept and the proposed unmanned ship is that there will be no duty engineer to respond to alarms and correct problems, meaning that even easily repairable at sea failures can seriously affect the operation of the ship.

In the case of the unmanned ship propulsion plant, the Mean Time to Failure (MTTF) was assumed as being the Mean Time Between Failures (MTBF) for repairable at sea failures in a manned plant, while the MTTF for non-repairable at sea failures was considered for the manned propulsion system. It is then obvious that extra redundancy will have to be included in the totally unmanned propulsion plant in order to achieve the same failure rate.

A number of different system architectures with different types (gas turbines and diesel engines) and a different number of prime movers have been considered, as seen in Figure 40 including both mechanical and electric transmission.

It is important to note that although fuel cells have a great potential to operate unmanned [83], their use was not considered in this thesis, since the lack of experience in operations at sea and the impossibility to obtain reliable failure rates data would not permit a thorough reliability analysis or a comparison between this prime mover and the well established diesel and gas turbine systems.

As a benchmark for this analysis, a conventional propulsion plant consisting of a medium speed diesel engine connected to a controllable pitch propeller through a gearbox will be used. Two high-speed diesel generators providing electric power to the ship complement the system.

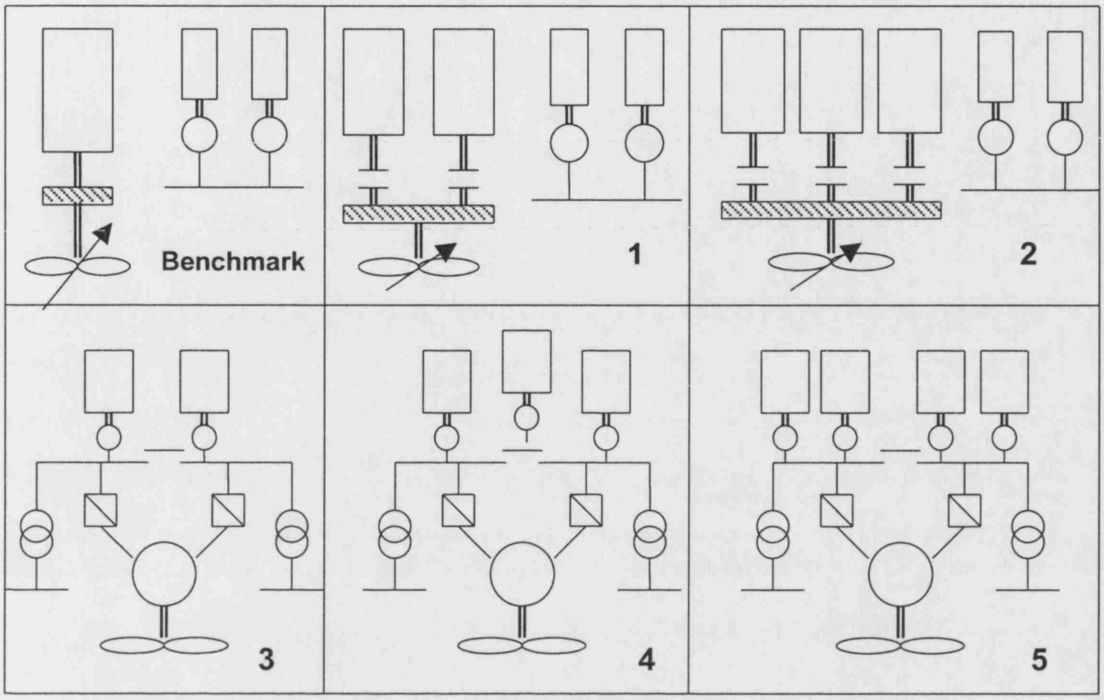


Figure 40 – Propulsion Options Considered

Some assumptions were made in this analysis, as explained in the following paragraphs:

a) A constant failure rate λ was assumed for each equipment and an exponential reliability time distribution (R(t)) was used in the calculations, where:
- $R(t) = e^{-\lambda t}$, where
- $\lambda = 1/MTTF$

b) The failure of any item was considered to have no effect on the probability of failure of other items, i.e. all events in the system were considered as independent.

Obtaining reliability data [63][64][65][66] for all the main items in the propulsion options considered was very difficult, since it is very unlikely to find two independent references giving similar values for the same equipment.

The problem lies in part in the different operation experience of the sources and sometimes resides in the definition of failure itself.

Regarding the prime movers, however, which are the main sources of failure in a propulsion plant, three references with considerable experience in both gas turbine and diesel engine operation -- Royal Navy [67], U.S. Navy [68] and Brazilian Navy [69] – provided very similar reliability data.

Diesel engines tend to attract a fairly large amount of maintainer's time to keep them in an operating condition. By virtue of the large part count and vibration, in comparison with a gas turbine, low tech failures (fasteners coming loose, leaks etc) that can be easily fixed tend to dominate in general operation, leading to the quoted 500 hours between repairable at sea failures [67].

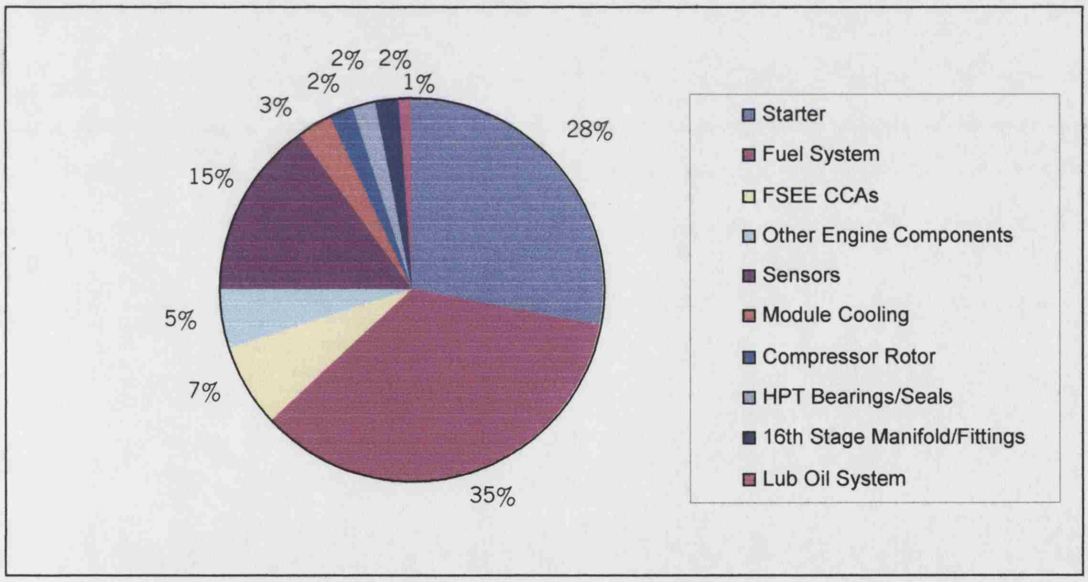


Figure 41 – LM 2500 Failure Modes [70]

With respect to gas turbines, the U.S. Navy provided the worst MTTF of 800 hours, but is currently implementing a programme to increase this number to 3000 hours, focusing in the main sources of failure.

All three organisations, however, indicate the starting system as having a high failure rate, as can be seen in Figure 40, driving MTTF values down. It is then reasonable to imagine that by starting the gas turbines prior to the ship leaving the berth, a lower risk of failure at sea could be achieved.

This possibility was not considered in this analysis, since the contribution of the starting system varies for each Navy and the values used in the calculations can be seen in Table 9 and, as explained in the previous paragraphs, can only be considered for a relative comparison.

Item	MTBF / MTTF (hours)	Item	MTBF / MTTF (hours)
Diesel (manned)	2700	Diesel (unmanned)	500
GT (unmanned)	1000	Gear	133,000
Thrust Bearing	100,000	Shafting & Bearings	275,000
Stern Tube	275,000	Alternator	30,000
Electronic Converter	20,000	Transformer	300,000
Propulsion Motor	50,000	CPP	13,500
Circuit Breaker	1,000,000	Bus Short Circuit	1,000,000

Table 9 – Reliability Data

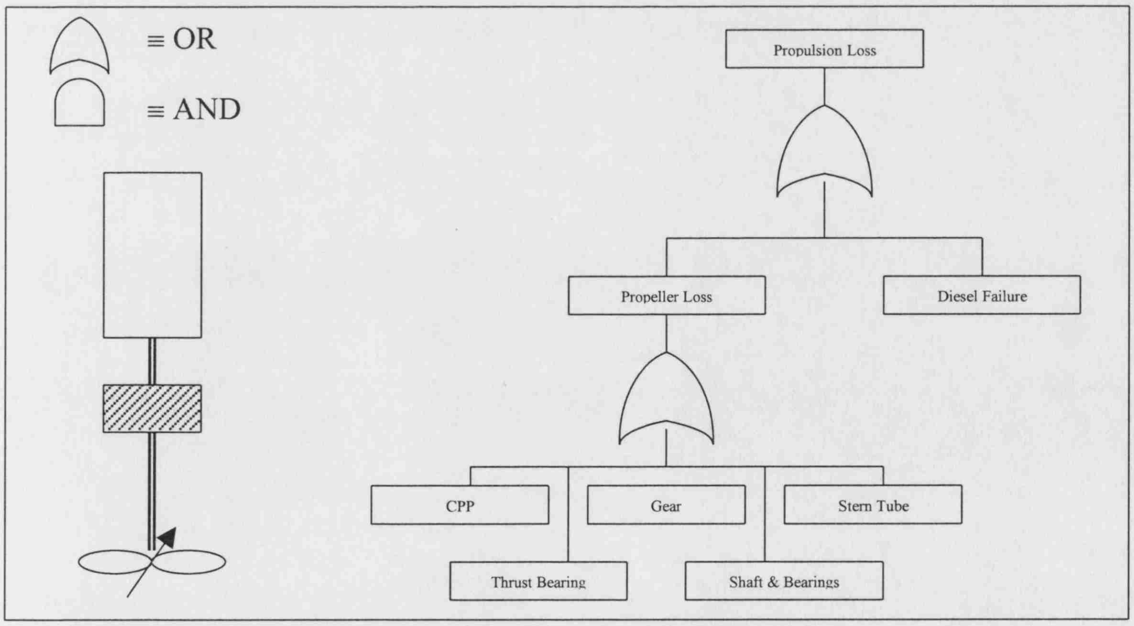


Figure 42 – Fault Tree – Benchmark

A reliability analysis of the propulsion options listed in Figure 40, in the case of total propulsion loss, was then carried out using Fault Trees, such as the ones shown in Figure 42 for the benchmark and in Figure 43 for the simplest electric propulsion configuration.

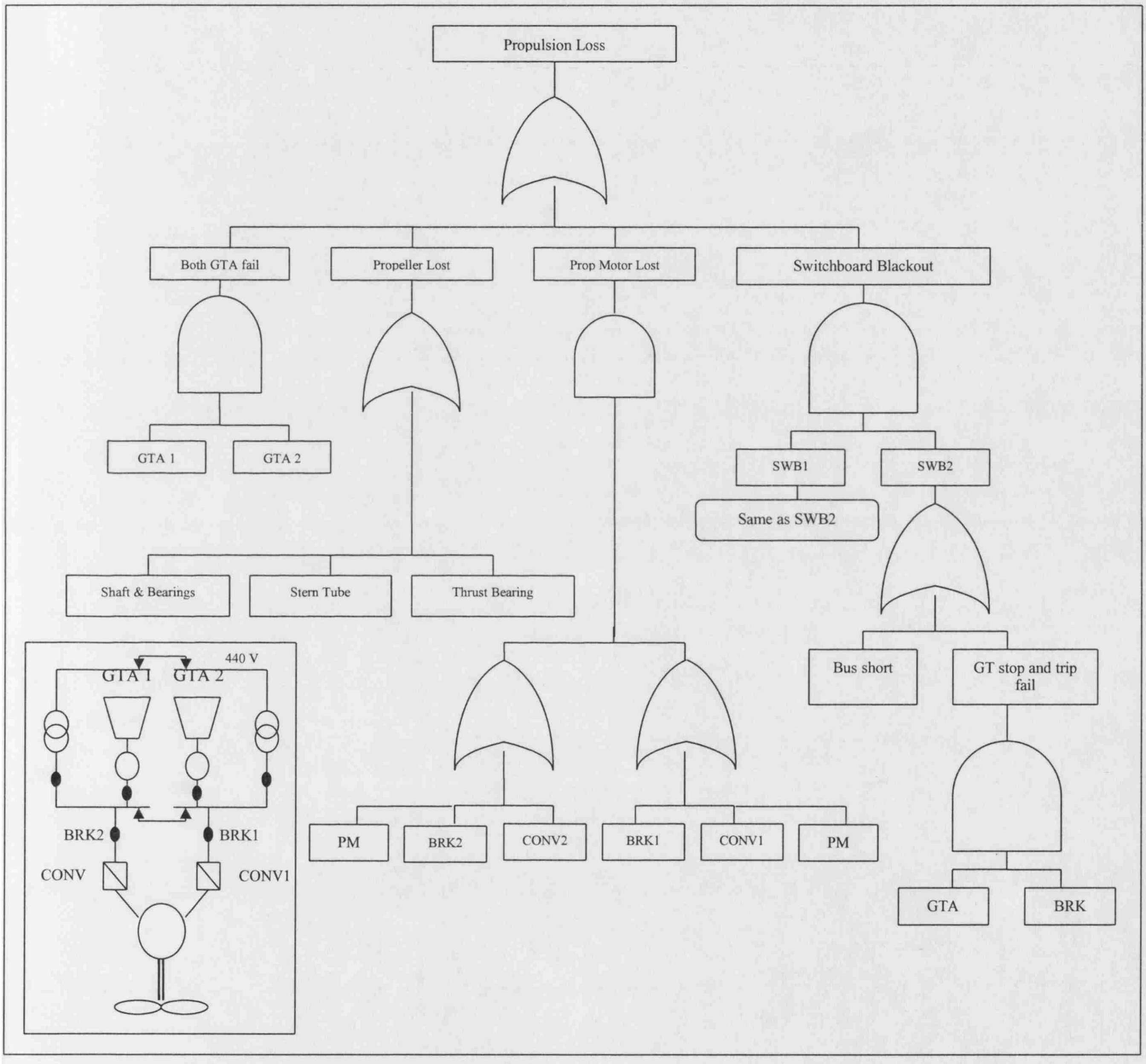


Figure 43 – Fault Tree – Electric Propulsion

Details of the procedure used in the reliability study, as well as examples of the calculations performed can be seen in Annex 4. The failure rate was evaluated for each of the configurations considered and the final result can be seen in Figure 44.

As an example, “Mechanic 2D” represents the unmanned mechanic propulsion system with two diesel engines and “Electric 2GTA” represents the unmanned electric propulsion system with two gas turbine generators.

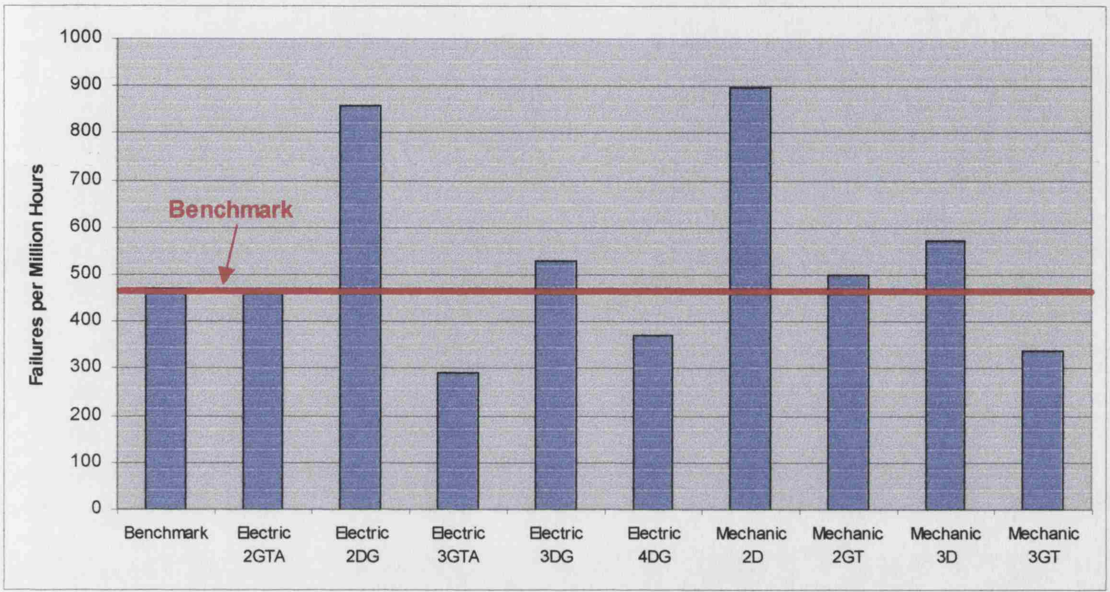


Figure 44 – Failures per Million Hours for Different Propulsion Options

The following conclusions can be drawn from the reliability analysis result and will form the basis for the selection of a suitable propulsion system for the unmanned ship with a failure rate below the defined benchmark.

a) When diesel engines are used, at least four prime movers are required in an electric propulsion configuration. In a mechanic architecture, at least six diesel engines would be needed, with four of them for the propulsion in a CODAD[14] configuration. This last option was not considered due to the complexity of the system, allied to the expected high maintenance cost and difficulties in accommodating the prime movers in the engine room.

b) Traditional mechanic propulsion would only be possible if three gas turbines are used as prime movers in a

[14] Combined Diesel And Diesel

COGAG[15] configuration, with the system complemented by two extra generators.

c) By using an electric propulsion concept, it is possible to achieve a failure rate slightly better than the benchmark with only two gas turbines generators for both propulsion and electricity generation.

[15] Combined Gas And Gas

6.3 Maintenance Philosophy

In this section, only the expected differences in maintenance practices inherent to the operation of an unmanned vessel will be presented.

The evolution and use of concepts such as Condition Based Maintenance (CBM), remote diagnostics and the use of smart sensors, although seen as highly desirable when operating such a ship, will not be discussed, since they also apply to conventionally manned vessels and the technology used will be basically the same.

Maintenance work on board the unmanned ship will only be possible during port visits, which will limit the applicability of this concept to vessels with operation profiles contemplating suitable times moored with more frequent port visits.

The use of aviation industry maintenance practices is probably ideal for the unmanned ship, since they rely almost exclusively on ground teams that perform visual inspections and carry out any required maintenance work every time an aeroplane stops in an airport.

The "upkeep by exchange" policy can also be adopted and special attention during an unmanned ship design must be given to removal routes of bulky equipment.

Feeder ships of various types already have an operation profile very similar to a long-haul commercial aeroplane, with leg lengths of around 12 hours, and this maintenance philosophy could be easily adopted.

There has been a recent shift from the established practice of major airlines doing their own aircraft maintenance towards more contracting out and the growth of third party maintenance services, leading to a major reduction in cost [57], a practice that could be adopted in an unmanned ship operation.

6.4 Summary

A number of unmanned propulsion systems as reliable as a conventionally manned plant was presented and maintenance philosophies were discussed.

The following conclusions can be drawn from this chapter:

- The introduction of redundancy and/or flexibility in a propulsion plant can provide unmanned systems with expected failure rates below those likely to be found in conventionally manned engine rooms currently in operation at sea;

- The inherent characteristics of flexibility and interoperability of electric propulsion plants appear to be highly desirable in the unmanned system design, since it was demonstrated that it could provide a solution comprising only two prime movers, while a traditional mechanic configuration would require at least five

- Vessels with operation profiles characterised by short leg lengths and relatively long periods moored, such as feeder ships, could adopt aviation industry maintenance practices, relying on "ground maintenance teams" and "upkeep by exchange" philosophy.

CHAPTER 7

COMMUNICATIONS, SAFETY AND SECURITY CONSIDERATIONS

7.1 Introduction

As previously mentioned, the objective of this thesis is to propose a new concept of ship design and operation that will be at least as safe and reliable as conventional ship currently at sea.

In order to achieve that, a number of different arrangements must be fitted on board the unmanned ship to deal with possible incidents caused by equipment failures at sea, such as total propulsion loss, fire, etc.

As far as communications are concerned, the unmanned ship must have sufficient capability to enable interaction with other ships and shore stations using the systems and frequencies currently in use at sea, as defined by SOLAS.

The need of a ship-shore data link, providing system health information to the control centre as well as allowing remote control of the ship is also discussed.

7.2 Towing Arrangements

In case of failures leading to the loss of control of the vessel, arrangements must be provided to permit the ship to be towed without the need to have someone on board.

A device, similar to the Emergency Towing Arrangement required by SOLAS to be fitted in tankers of 20,000 tons deadweight and upwards, constructed on or after 1996, could be used aft and forward on board the unmanned ship.

In this system, a pick-up gear, consisting of a marker buoy, a pick-up rope and a messenger rope, is stored in a box on the deck, in a way that it can be easily deployed in case of emergency.

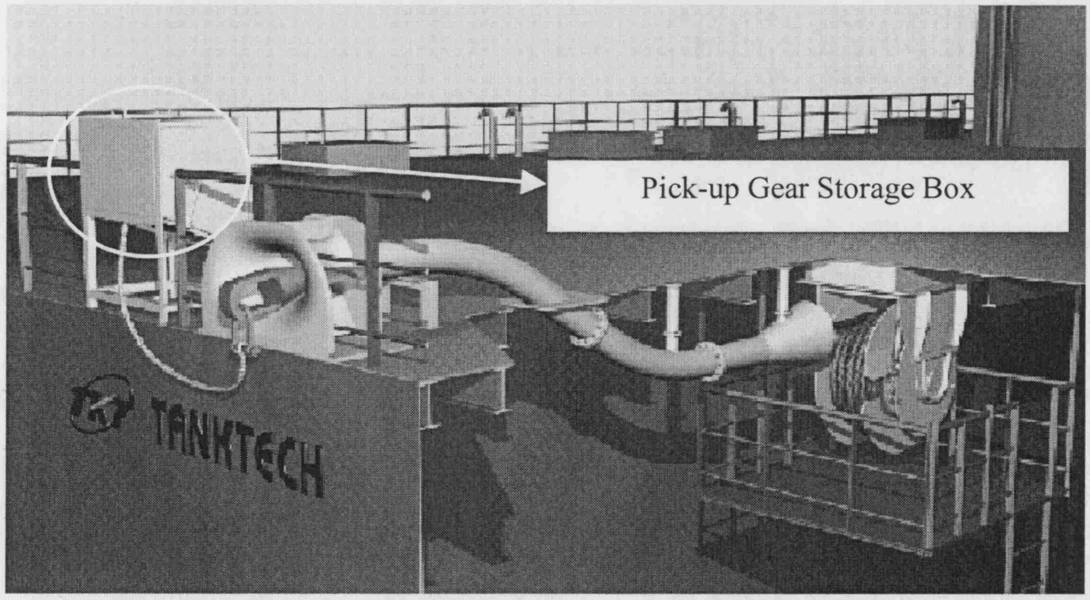


Figure 45 – Emergency Towing Arrangement [49]

If arrangements are made in order that the pick-up gear can be released by remote control, the same system shown in Figure 45 could be used on board the unmanned ship.

7.3 Fire Inhibition

The elimination of flammable objects related to the comfort of the crew, such as kitchen appliances, decoration, linings, clothes, linen, etc is per se a factor that will contribute to enhanced safety on board, as far as fire is concerned.

The use of sophisticated fire detection systems, already in use on board cruise ships and naval vessels, combined with a fixed fire-fighting system was initially investigated.

The procedures adopted by vessels with this kind of configuration determine that every fire alarm must be investigated in loco before activating the fixed fire-fighting system, which would be impossible in an unmanned ship.

The main reason for this procedure is that fire detection devices are known to produce a reasonable incidence of false alarms, especially in compartments containing heat-generating equipment, and the activation of fixed fire-fighting systems, usually based on CO_2 or water mist, can cause heavy damage to the equipment contained in the protected compartment.

In the unmanned ship, however, fire-fighting systems can be substituted by a fire inhibition concept, where the necessary conditions to start a fire are avoided.

Figure 46 – Fire Triangle

It is well known that a fire will only occur if all the elements of the so-called fire triangle are present at a suitable level, i.e. heat, fuel and oxygen.

Although a careful segregation of combustible material from heat sources is extremely important to reduce he risks of fire on board a vessel, it is very difficult, if not impossible, to completely eliminate that risk. Oil leaks or fumes in an engine room, as examples, can travel trough unpredicted paths and get in contact with heated equipment, creating a perfect condition to start a fire.

The elimination of the last element of the fire triangle – oxygen – on the other hand, can be a very effective way of eliminating the risk of a fire in a compartment.

Since the ship being proposed is designed to operate unmanned, a concept similar to the inerting of cargo tanks on board oil/chemical tankers and gas carriers, where oxygen levels are kept below a preset level (around 6%) to avoid combustion, can be used throughout the vessel.

7.3.1 Inert Gas Systems (IGS)

Since the objective is to inert all internal spaces posing a high fire risk in the unmanned ship, the use of inert gas in bottles was discarded and an onboard autonomous inert gas generation system will have to be fitted.

Initially, an overview of some of the most common systems will be presented.

7.3.1.1 Fuel Fired Systems

The traditional fuel fired inert gas generator system, widely used on board oil tankers, supplies treated flue gas from main or auxiliary boilers.

The system will include at least a fan for the feed air, the fuel system, a burner and combustion chamber, a sea water pump and a scrubber to cool and clean the generated exhaust gas and blowers to distribute the inert gas and maintain the spaces to be protected under positive pressure.

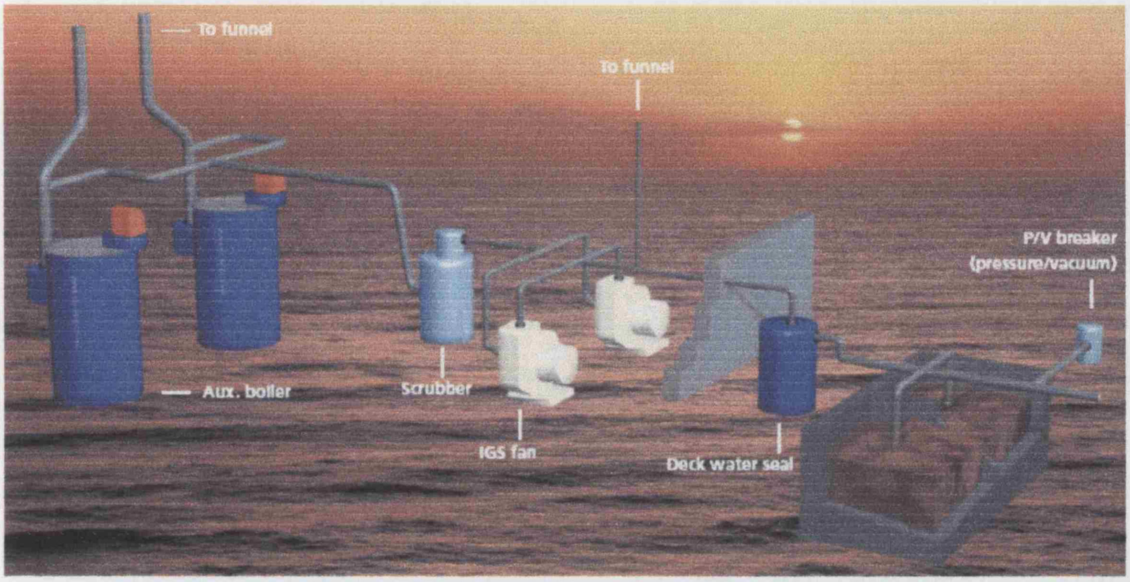


Figure 47 – Fuel Fired Inert Gas System [84]

The system requires a considerable volume inside the ship and is capable of generating inert gas with oxygen levels below 6%, but containing some impurities generated by the combustion in the boilers.

7.3.1.2 Pressure Swing Adsorption (PSA)

The principle of the PSA technology, usually used to generate nitrogen on board LPG carriers, is based on air separated in a bed with carbon molecular sieve where the oxygen molecules are adsorbed much faster than the nitrogen molecules.

For about one minute, until the carbon bed becomes saturated with oxygen, pure nitrogen will flow out of the system when pressure is applied. Once saturated, the carbon bed has to be de-pressurised and purged by some nitrogen product to remove the oxygen. At the same time, a second carbon bed is pressurised to maintain a continuous nitrogen flow.

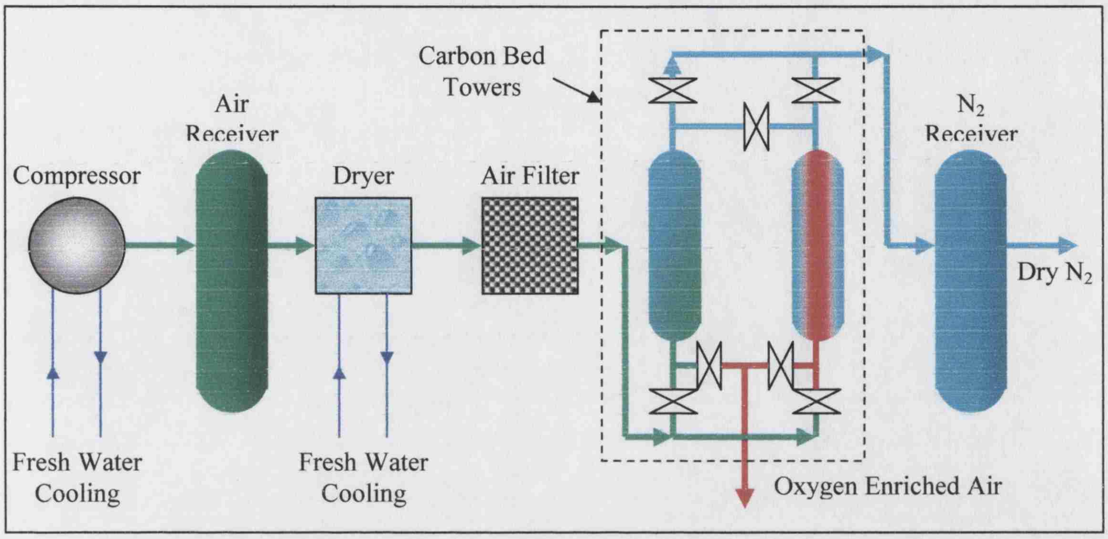


Figure 48 - Pressure Swing Adsorption (PSA) Inert Gas System

A complete PSA system, as seen in Figure 48, will include a feed air compressor, an air receiver to equalise the swinging air requirement, a refrigerated dryer, filter system, the two carbon bed towers and a nitrogen receiver to equalise the nitrogen purity.

The quality and the timing and control of the automatic valve operation of the inlet and outlet valves of the carbon beds are very critical to maintain the high purity of nitrogen.

The system can generate a clean supply of nitrogen with less than 1% of oxygen content

7.3.1.3 Membrane Type Inert Gas System

Compared with the traditional fuel fired inert gas generators or the PSA type of nitrogen generators, the simplicity of the membrane nitrogen systems is remarkable, as seen in Figure 49.

The system works by separating air into its component gases by passing compressed air through a bundle of hollow fibre, semi-permeable membranes. The membrane divide the air into two streams, one is essentially nitrogen and the other oxygen plus carbon dioxide and other trace gases.

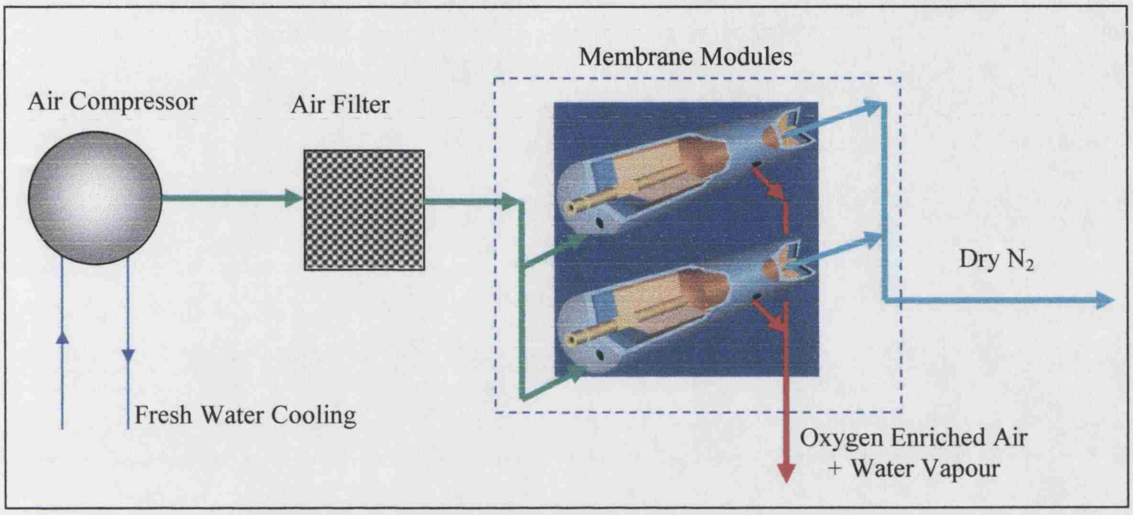


Figure 49 – Membrane Type Inert Gas System

The system works by separating air into its component gases by passing compressed air through a bundle of hollow fibre, semi-permeable membranes. The membrane divide the air into two streams, one is essentially nitrogen and the other oxygen plus carbon dioxide and other trace gases.

Clean and dry nitrogen is provided by a standard screw compressor and a second unit, containing the feed air pre-treatment, membranes, and control systems.

The entire system consists of only these two components and is capable of generating an inert gas with less than 1% of oxygen content.

The weight and physical size of the membrane system are also very attractive when compared with a PSA nitrogen generator system, as shown in Figure 50.

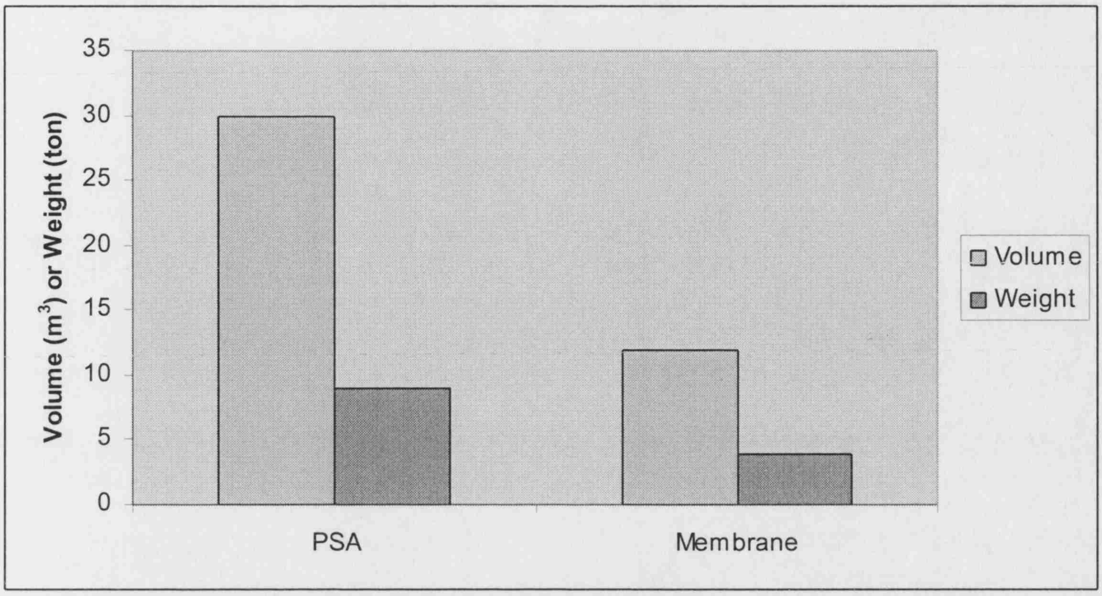


Figure 50 – Comparison for a 400Nm^3/h @ 99.9% Purity IGS [85]

The system is already designed for autonomous operation, which allied with its simplicity make it an attractive inert gas generation technology to be operated unmanned.

7.3.2 Atmosphere Control

The design is to provide a system capable to withstand operational conditions similar to the "closed down" configuration used in naval vessels during a Nuclear Bacteriological and Chemical Warfare (NBCW) threat, where machinery intakes and exhausts are enclosed and it is possible to re-circulate the compartment air through chilled water coolers and isolate the machinery spaces from the external ambient air.

In the case of the unmanned ship, the isolated compartments will be flooded with Nitrogen generated by a Membrane Type generator presented in the previous section.

UK MOD Naval Engineering Standards (NES) [86] and Lloyd's Naval Rules [87] were used to establish the requirements of this system, represented in Figure 51.

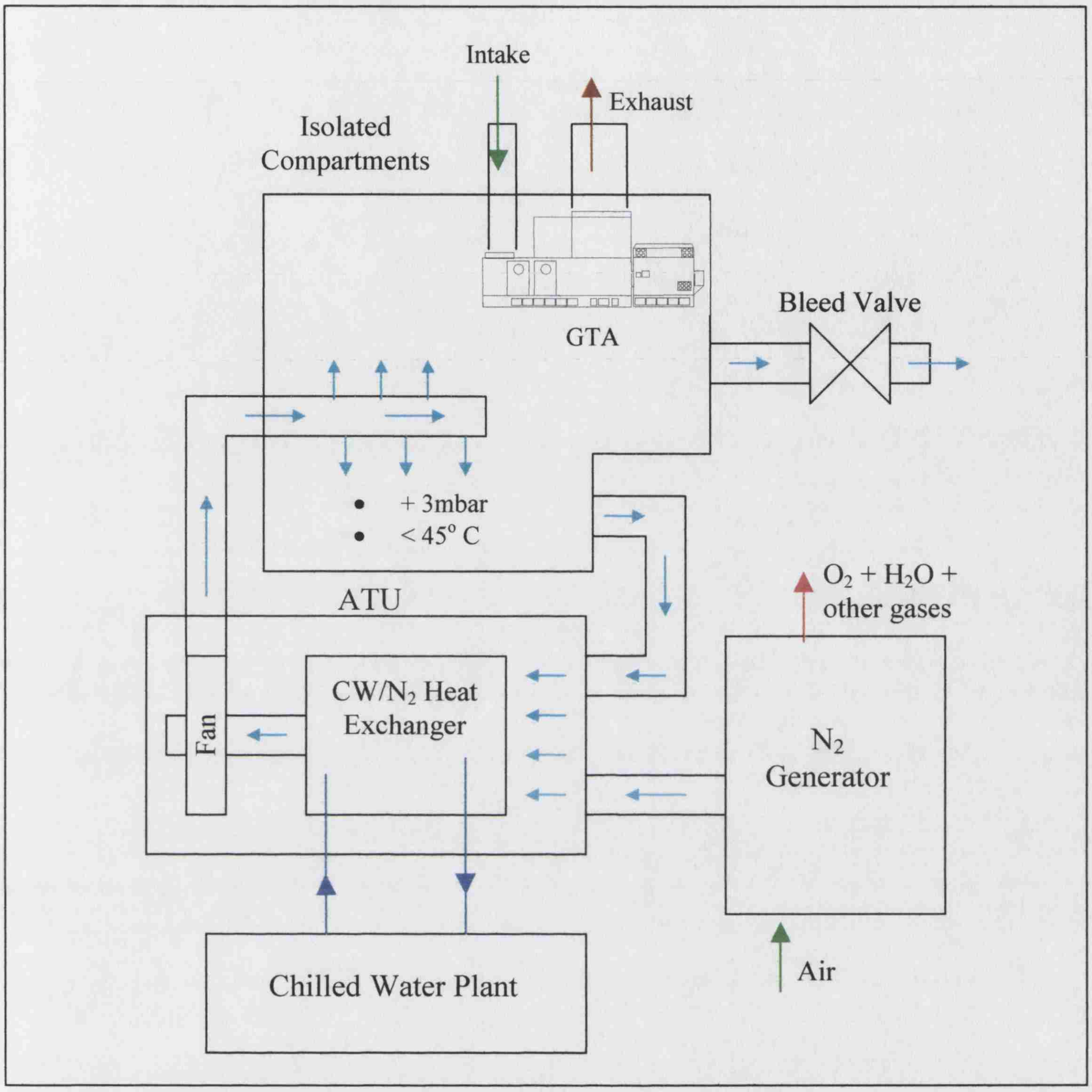


Figure 51 – Closed Down Operation Philosophy

The heat exchangers are to be sized to ensure that when operating at full power, with machinery and electrical items running simultaneously, the maximum temperature within the isolated spaces will not exceed 45°C.

It is essential that heat is not allowed to build up in isolated `hot spots' with the possibility of damaging electric cables, etc., and the location of distribution terminals is therefore critical.

In this state a positive pressure (normally 3 millibars above ambient air pressure) is to be created and maintained in the isolated spaces by introducing a quantity of inert gas, calculated by the summation of any known controlled losses and the calculated uncontrolled leakages based on a loss of 0.5 air changes per hour on the gross volume of the spaces.

To ensure that the pressure within the spaces does not build up above the desired limit, non-return bleed valves, set to open at 3 mbar above atmospheric pressure are to be fitted. These valves will be set to pass the balance between the supply inert gas quantity and the combined controlled losses, if any, and the calculated uncontrolled losses from the space.

The nitrogen-flooded zone will also be subdivided in smaller airtight compartments in order to permit venting to the atmosphere of a specific compartment, when maintenance work in port is required in any equipment contained in that compartment.

Once again, the use of gas turbines as prime movers is better suited for this application, since they can be mounted in a sealed enclosure that provide thermal attenuation, as well as interfaces for required ship supplied services, such as electrical power and start air.

All the intake air required by the gas turbine for combustion ($\approx 28\%$) and cooling ($\approx 72\%$) is collected from the inlet ducts and remains contained within the enclosure until expelled through the exhaust ducts, ideally without leakages to the engine room.

The enclosure is usually also fitted with a dedicated fire fighting system using inert gases or water mist sprinklers designed to contain the fire within the enclosure boundaries.

7.4 Ship-Shore Data Link

The unmanned ship systems, as described in the previous chapters, are designed to operate totally independent from human interference.

The inherent unpredictability of any operation at sea, however, makes it very attractive to have remote control capabilities over the vessel, as a backup for all the automated systems, not only in the berthing phase, as described in Chapter 5, but in the other phases of navigation.

Apart from that, the control centre from where the operation of the unmanned ship will be managed will need a constant update of information such as health diagnostics and position fixing.

A number of wireless remote control options were investigated, but the only commercially available technology capable of operating beyond the line of sight appears to be a satellite-based computer network.

Near real time remote control using the Internet is already possible and well proved, as can be seen and experienced by anyone by visiting a number of websites [93].

The bit rates commercially available today, however, limit this technology to applications where rapid reactions are not essential, or where only a limited number of parameters are controlled.

Internet or intranet access at sea is already commercially available as part of a mobile office at sea concept, although with a number of limitations and operating at a low bandwidth (up to 64 kbps [90]).

In the next few years, however, a revolution in global communication is expected when Teledesic, a company backed up by names such as Microsoft Chairman Bill Gates, intends to initiate operation providing global communication links via a constellation of 288 Low Earth Orbit (LEO) satellites [91].

This system, expected to enter service in 2006, will operate as a network operator and will support communications ranging from high-quality voice channels to broadband channels supporting videoconferencing, interactive multimedia and real-time two-way digital data flow, providing fibre-optic like links to customers around the world, including the maritime market.

With this system, bit rates of up to 2Mbps will be available, giving a new dimension to the concept of remote control.

This new technology is ideal for an application such as a backup control mode for the unmanned ship, making it possible to replicate all information that would be available in a conventional bridge or engine control centre in a control centre located anywhere in the world.

The company has not determined the cost of the system for the final users yet, but their goal is to be competitive with conventional land-based high bandwidth services [91].

7.5 Communications

In accordance with SOLAS Chapter IV, every ship must be capable of:

- Transmitting ship-to-shore distress alerts by at least two separate and independent means, each using a different radio communication service;
- Receiving shore-to-ship distress alerts;
- Transmitting and receiving ship-to-ship distress alerts;
- Transmitting and receiving search and rescue co-ordinating communications;
- Transmitting and receiving on-scene communications;
- Transmitting and receiving signals for locating;
- Transmitting and receiving maritime safety information;
- Transmitting and receiving general radio communications to and from shore-based radio systems or networks; and
- Transmitting and receiving bridge-to-bridge communications.

Since the unmanned ship would not have resources on board to act as a safe haven to people in distress at sea, the requirements linked to search and rescue (SAR) become meaningless.

The ship could, however, participate in SAR operations by relaying any received distress alert to other ships in the area and to shore.

The requirements for the unmanned ship would therefore concentrate on ship-to-ship-to-shore voice and data communications, mainly "bridge-to-bridge" communications and maritime safety information exchange.

A system frequently used on board aircraft carriers to eliminate the risk of premature firing of ordnance or explosion of their warheads during loading and offloading operations due to radio frequency radiation.

The hazard to electronic explosive devices occurs because of the heat generated by a current passing through the sensitive wires surrounding a temperature-sensitive explosive. If energy is dissipated into the wires, current will flow, the explosive will become hot, and an explosion can result.

When ordnance or their warheads are loaded, unloaded, or transferred, shipboard hazardous electromagnetic radiation (HERO) conditions may sometimes prohibit the transmission of radio frequency energy below 30 MHz (HF).

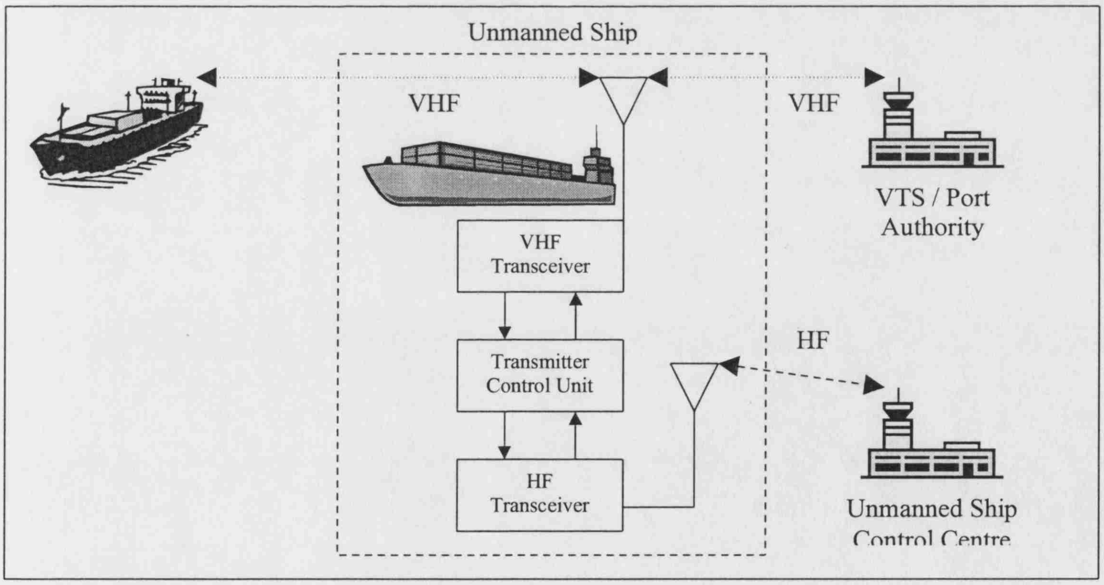


Figure 52 – Unmanned Ship Communications System

During such operations, all HF transmitters must be secured to prevent possible detonation of the ordnances and to maintain its ship-shore communications, the vessel transmits to a relay ship via a VHF circuit and the relaying ship retransmits the signal on a HF circuit to shore.

A very similar system, represented in Figure 52, can fulfil the requirements of ship-to-ship-to-shore communications defined by SOLAS, allowing a perfect integration of the unmanned ship with established communication procedures in use at sea.

The primary system, however, would use the same concept, but using the satellite communication link described in the previous section, leaving the HF link as a backup.

7.6 Piracy and Terrorism

The resurgence of violent piracy as a modern-day threat and the recent terrorist attacks inflicted upon targets all over the world are factors that have to be taken into consideration when designing any ship and the vulnerability of the unmanned ship in those matters has to be assessed and compared with a conventionally manned vessel.

There were 2,375 registered incidents of piracy around the world between 1991 and 2000, with annual reports ranging from 100 up to the maximum of 469 in 2000 [93].

Although these figures may understate the true dimension of the problem, since most attacks go unreported due to the possibility of delays caused by investigations and increase in maritime insurance premiums [94], they help to define some characteristics of the modern piracy activities:

- Southeast Asia accounts for 57% of the reported incidents, followed by Africa (13%), Americas (13%), the Indian Subcontinent (12%) and rest of the world (5%);

- Incidents range from opportunist low-level theft of vessels at anchor to the hijacking of ships, for future fraudulent register under flags of convenience;

- 2,058 mariners were taken hostage, 280 killed, 275 seriously injured and 137 physically assaulted.

From these numbers, the constant feature in piracy attacks appears to be the violence against the crew, which is reflected in guidelines and recommendations issued by organisations such as the International Maritime Council and International Maritime Organisation, which strongly emphasise avoiding armed confrontation, suggesting that the best action to be taken by the crew is to inform port authorities and nearby vessels.

It becomes clear from those guidelines that the presence of a crew on board a ship becomes part of the problem rather than a possible solution, which could mean an extra advantage in favour of an unmanned ship.

As far as terrorism is concerned, the International Maritime Organisation is working on new regulations and guidelines to be finalised by the end of 2002 [4], with propositions concentrating on a thorough investigation of seafarers and the creation of a security culture among ocean going crews.

Proposed crew responses, however, are very similar to those already mentioned regarding piracy, giving them a passive role if terrorists take over their vessel.

The remote control capabilities of the unmanned ship can provide new solutions during a terrorist attack, since innocent seafarer lives would not be at risk.

7.7 Summary

Safety issues connected with the absence of a crew on board the unmanned ship were highlighted and solutions were proposed, as follows:

- A remotely operated Emergency Towing Arrangement, similar to those required by SOLAS to be fitted in some oil tankers, will allow the unmanned ship to be towed in case of total propulsion loss or other emergency;

- A fire inhibition concept was introduced, consisting in flooding areas posing a high fire risk with inert gas generated on board, eliminating one of the elements of the fire triangle;

- An atmosphere control philosophy based on the "closed down" configuration used in naval vessels during a Nuclear, Bacteriological and Chemical Warfare threat was adopted in the inerted compartments;

- The requirement of a high bandwidth ship-shore data link was presented in order to provide a remote control capability in case of failure of critical automated systems and a suitable solution was presented;

- A communication system was designed to integrate the unmanned ship into the ship-to-ship-to-shore communication structure currently in use at sea, with VHF transmissions being relayed via different frequencies to a control centre ashore.

CHAPTER 8

THE SHIP

8.1 Introduction

The main areas of the operation of the unmanned ship, such as navigation, propulsion and communications, have been discussed in the previous chapters, where the equipment needed for the satisfactory performance of each subsystem, as well as their limitations, have been identified.

At this point, the operation of an unmanned ship appears technologically viable, provided that the constraints established in the previous chapters are observed.

In this chapter, a state of the art ship currently in operation will be selected as a benchmark and the design of an unmanned ship with approximately the same main hull will be developed, which will lead to a direct comparison between both concepts.

8.2 The Benchmark

In the previous chapters, it became clear that the concept of an unmanned ship couldn't be applied to every type of ship in every area of operation.

Some ships can be immediately discarded, such as passenger ships where most of the advantages of not having a crew on board would disappear, apart from the fact that one would not expect that passengers would feel comfortable without the figure of a captain in charge of the ship.

Other ship types, although not limited by technical constraints, should also be discarded at this point where the concept is trying to be proven. Oil tankers, chemical tankers and gas carriers, due to the environmental risks posed by their cargoes would probably make the concept unacceptable before fully proven in other ships.

Bulk carriers were also eliminated because they usually need constant maintenance and repair in the structure, since discharge processes using grabs or similar equipment commonly inflict some damage in their holds. It is very common to find fitters listed in the crew list of such vessels, carrying out these repairs while the ship is at sea in ballast condition.

Of the main types of ships, the choice was between a general cargo ship and a containership.

Containerised cargo has been the fastest-growing portion of international trade over the last 30 years and is likely to remain so. As shown in Figure 53, over the last years, the average annual growth in the containership fleet has been 8.8 percent per year. Over the same time, the capacity of the general cargo vessel fleet has decreased by an average of 6.9 percent per year, as those vessels have become less profitable to use in serving ever-specialised (and containerised) cargo shipping markets [51].

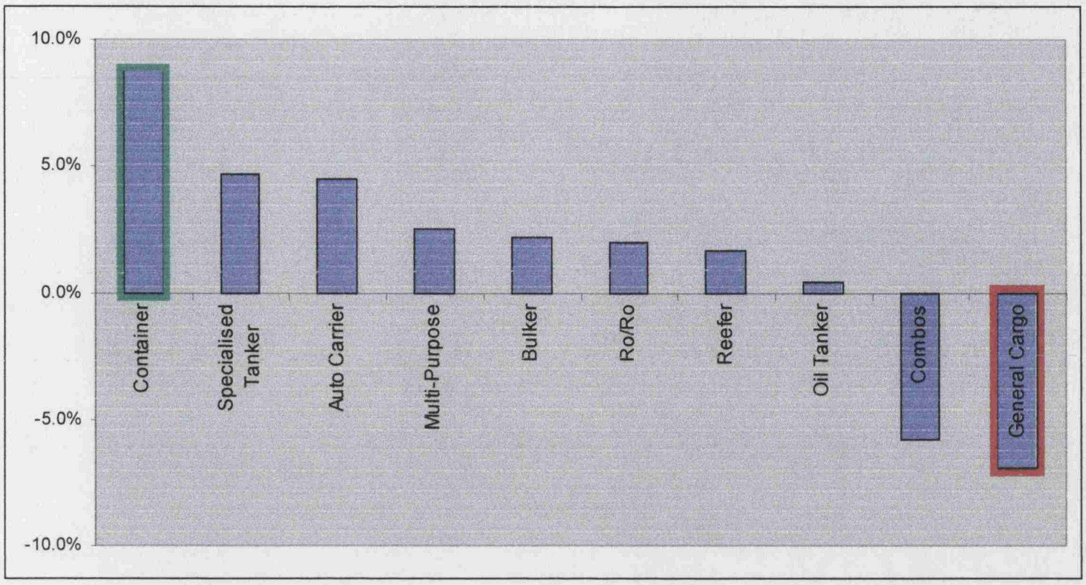


Figure 53 – Average Annual Percentage Change in World Fleet (1985 – 2000 in Dwt)[51]

This growth rate, faster than overall trade in general, is the result of several factors, which also make containers ideal for the concept of an unmanned ship, since they:

- Provide security and safety;
- Can be moved as a unit, thereby providing greater efficiency at ports and require little or no action by the crew.

Having decided the type of ship, it is now necessary to establish the ideal sizing, considering not only the conclusions stated in the previous chapters but also the market trends of containership operation.

As it was stated in Chapter 3, there is no correlation between the TEU capacity of a containership and its complement. Therefore, crew size, although directly linked to the potential savings that can be achieved by the implementation of the unmanned ship concept, is not a good parameter to define the selection criterion of the ship.

What could be observed from data obtained for a number of vessels through Significant Ships from 1995 – 2000[61], however, is that there is a clear trend in the superstructure proportion (Vs) in containerships, as can be seen in Figure 54. Since most of the equipment and volume associated with the crew is located in the superstructure, it is reasonable to assume that the superstructure proportion is a good parameter to estimate the potential advantages on an unmanned ship.

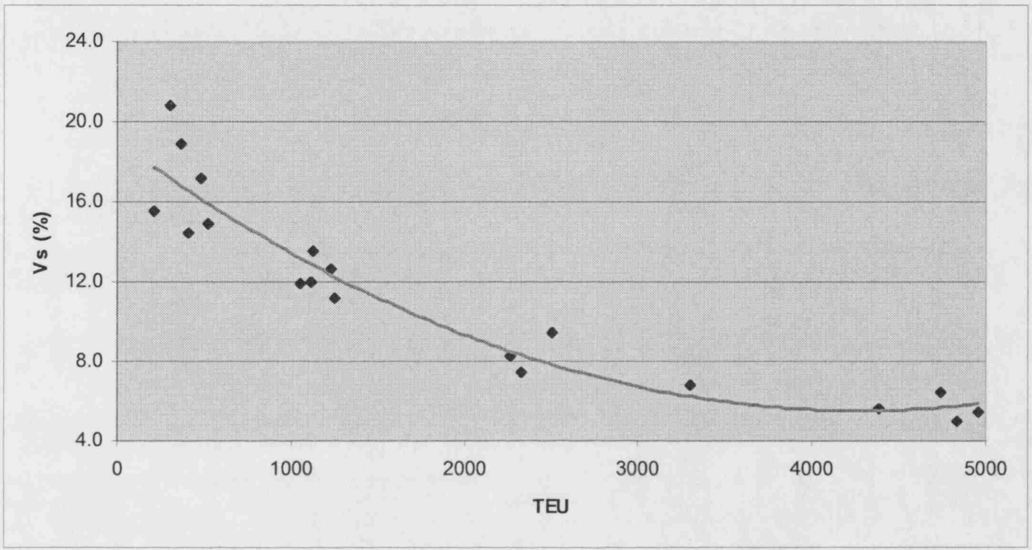


Figure 54 – Superstructure Proportion Trend in Containerships

By analysing the figure above, it becomes clear that the advantages of an unmanned ship can be maximised if a smaller ship is selected.

It is also apparent that there is a promising market for small containerships in the near future, as discussed in the next paragraphs.

In the shipping industry, the major carriers are constantly looking for ways to drive down the unit cost of moving a container, which was achieved by transporting more containers into larger ships. The first generation of containerships (in the 1960's) carried 600 to 800 TEU. By the late 1970's, ships with a capacity of 2,000 TEU were common.

The newest ships in the Europe-to-East Asia trade are rated at 6,000+ TEU. A leading industry consultant predicts that by the year 2010, a third of all container traffic will be carried on ships of more than 4,000 TEU. These very large ships can reduce the "per-slot" cost of transporting a container by as much as 50 percent [53].

Amortising the enormous capital costs of very large vessels means keeping them constantly on the move. As a result, ships have got bigger and the number of ports at which each ship calls has declined. Over time, the trend is thus for container traffic to be concentrated in a smaller number of larger ports.

It is then clear that an expansion in the feeder market is also expected in order to distribute the cargo discharged in a hub port by those mega-containerships to smaller ports.

It can also be observed in Figure 55 that containerships with capacities from 100 – 499 TEU, typically used in short distance feeder operations, have the oldest average age among the fleet. The average age of these small ships is 15.4 years, with 86 of 475 vessels in this category already 25 years old or older [51].

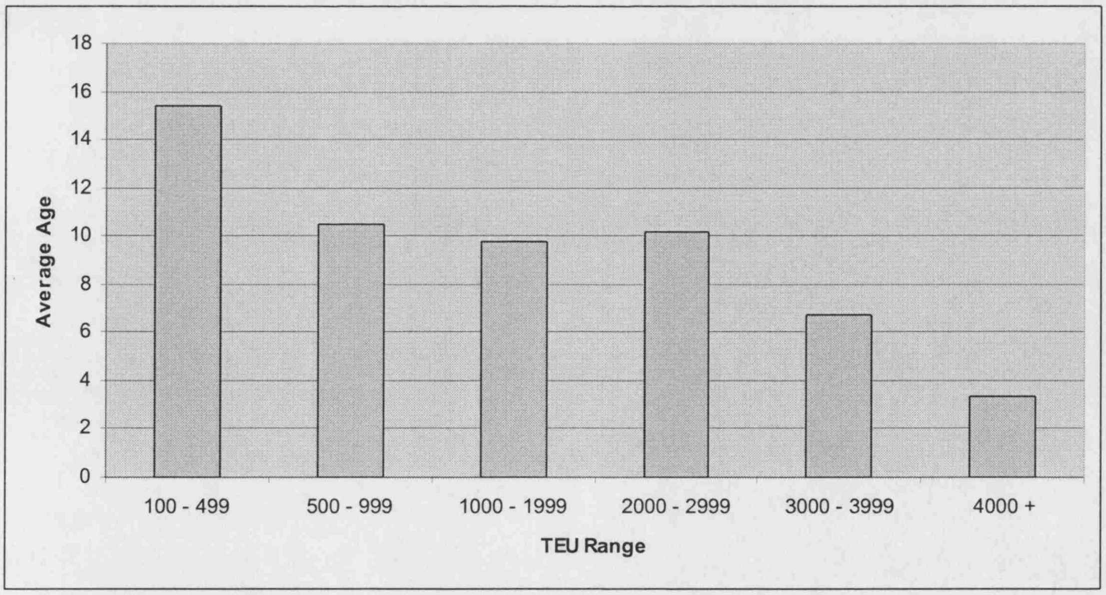


Figure 55 – Average Age Distribution of Containerships [51]

Although the maximum age for a containership is still evolving, it will normally become un-charterable over 25 years old [52]. It is therefore another good indication that the demand of smaller feeder vessels will increase in the next years.

A containership with a capacity ranging from 100 – 500 TEU was then selected and it was decided that the Conofeeder 300 (Figure 56 and Annex 16), quoted in the Significant Ships of 1998 would be the benchmark for the unmanned ship.

Figure 56 – Conofeeder 300 [54]

With a capacity of 301 TEU (equivalent to 191 TEU homogeneously loaded to 14 ton) and electrical connections for 50 refrigerated TEU, the gearless vessel can accommodate container sizes from 30 ft to 45 ft in two tiers in the hold, up to four on the hatch covers and up to five on the open deck above the engine room.

A 3280 kW Wärtsilä medium speed diesel engine is connected to a controllable pitch propeller through a gearbox and also provides a power take-off for a 500 kW alternator. Two 240 kW diesel generators complete the electrical plant that supply energy for hotel and cargo loads, as well as for a 300 kW bow thruster.

In terms of manning, the ship can be operated by seven people, although accommodation has been arranged for ten persons in a slim deckhouse aft.

After the selection of the ship, possible routes were investigated and although the area of operation of each ship of the Conofeeder 300 class was very distinct, the operation profile was quite similar.

Through the Internet [56], it was possible to identify the following routes:

Area	Round Trip	Max. Leg Length
Mediterranean Sea	7 days	≈ 16 h
West Atlantic	7 days	≈ 15 h
East Atlantic	7 days	≈ 30 h

Table 10 – Possible Routes

Figure 57 – Area of Operation

At random, the Mediterranean Sea option, providing a weekly Barcelona – Marseille – Barcelona – Valencia – Barcelona service, was selected but there is no reason why any of the remaining options could not be chosen.

8.3 Initial Sizing

Since an unmanned ship has never been built and no references of attempts to design such a ship have been found, it was impossible to obtain a validated algorithm or sizing procedure for this type of vessel.

It was decided that, the UCL containership design procedure [56], adapted to the size of the selected ship, would be used to generate a hull similar to the Conofeeder 300 and that the weight of crew related items as obtained through the procedure detailed in Annex 3, and the volume of the superstructure of the conventional ship would be considered as extra cargo to be transported by an unmanned ship, as seen in Figure 58, so that the same draught is achieved.

Figure 58 – Extra Cargo Transported by an Unmanned Ship

With the procedure detailed in Annex 3, the total weight of the crew related items for a ship with a complement of 10 seafarers was estimated as equivalent to 10 TEU homogeneously loaded to 14 tons.

The initial sizing consists of an iterative process, where the total weight, volume, dimensions and the installed power are estimated from a set of design requirements, ensuring that the dimensions of the ship are consistent with the number of containers required to be transported.

In this phase, the aim is basically to fulfil the following conditions:

- Total Weight = Displacement at desired waterline;
- Volume Available ≥ Volume required;
- Installed Shaft Power ≥ Power required for maximum speed;
- Fuel Capacity ≥ Fuel required for range.

From the information available in reference [61], in order to ensure a similar distribution of cargo on board and the same endurance, some parameters may already be set as constant, such as:

- Breadth = 15.85m
- Depth = 6.18m
- TEU capacity in holds = 72
- Speed = 15 knots
- Fuel Capacity was also kept constant at 273 m^3, although a much smaller volume would be required for the selected route.

The detailed calculation of the initial sizing can be seen in Annex 5 and the main results are listed in Table 11.

Ⓜ =	6.0	L =	100.80m
C_B =	0.609	B =	15.85m
C_P =	0.616	D =	6.18m
$P_{S(mcr)}$ =	2800 kW	T =	5.18m
Δ =	4865 ton	V =	10056 m^3

Table 11 – Initial Sizing

8.4 Parametric Survey

The aims of this part of the design is to investigate the effect of small changes in the form parameters obtained in the initial sizing and select the most efficient hull form in terms of procurement cost and fuel consumption.

At this stage, initial intact stability and freeboard are calculated, and consideration regarding the arrangement of containers is also given.

Examples of these calculations can be seen in Annex 6 and the following conclusions were drawn from the results obtained:

a) Considering the condition where 190 TEU homogeneously loaded are transported, it was observed that initial intact stability was not an issue in the range of form parameters considered;

b) When freeboard requirements were considered, it was determined that the length of the vessel must be limited to 100 m for the set of values studied

The remaining hull forms were then analysed in terms of through life cost, where only fuel and capital costs were considered.

A range of sensible fuel prices and interest rates experienced in the past five years was considered, which did not interfere with the shape of the graph seen in Figure 59, where the most economic ship is the one with the characteristics listed in Table 12.

Ⓜ =	5.50	L =	92.48	m	C_B =	0.665
k_B =	3.25	B =	15.85	m	C_P =	0.673
		D =	6.18	m	C_M =	0.988

Table 12 – Selected Characteristics

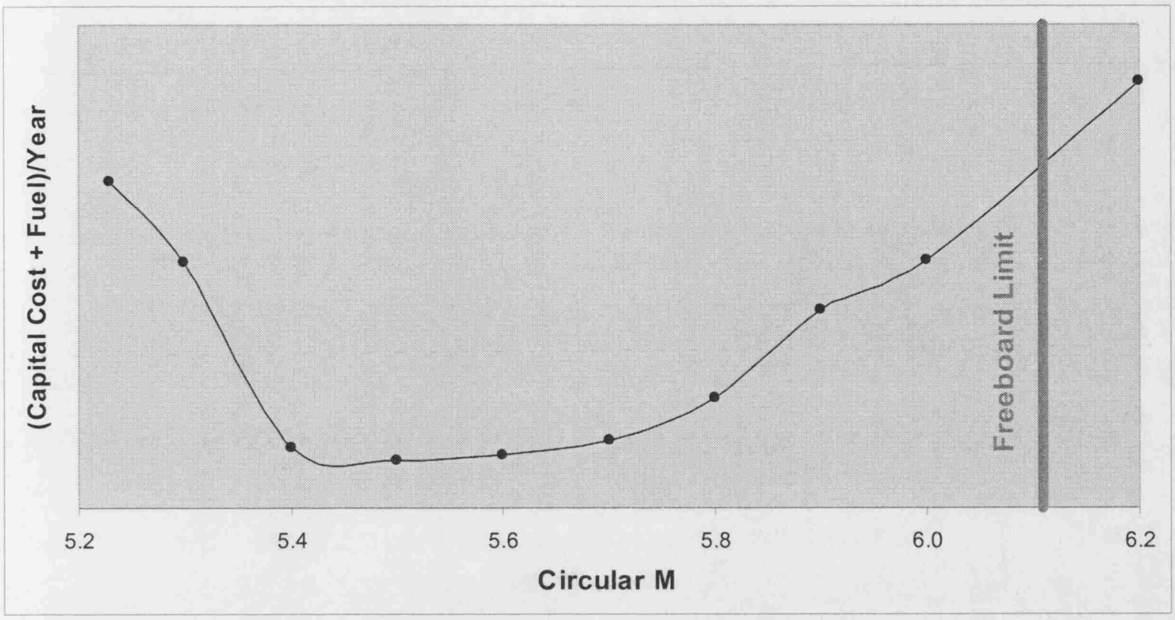


Figure 59 – Parametric Survey Results

8.5 Hull Form Design

The hull form was generated using the HULLPAK program [60] and small adjustments were made using AutoCad ®.

The hull can be seen in Annex 7, and Annex 8 indicates how the same number of containers transported in the holds by the Conofeeder 300 can be fitted in the generated hull, validating the design.

8.6 Power Requirement

The shaft power required for different speeds was obtained from Taylor Gertler data [58] and the results can be seen in Figure 60.

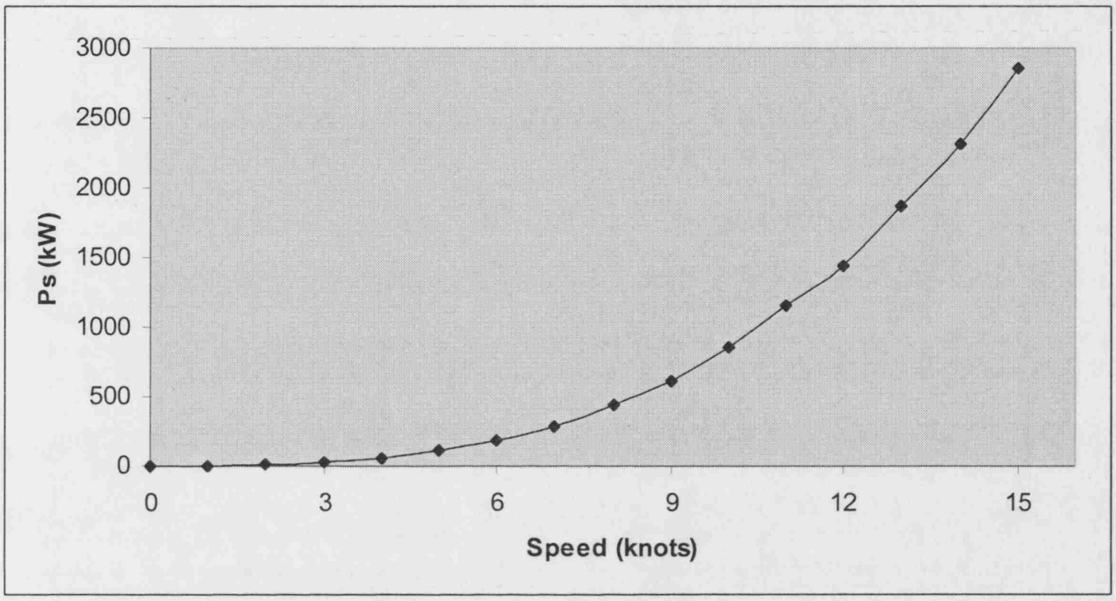


Figure 60 – Power x Speed Curve

8.7 Operation Profile

The distances involved in the selected route are [70]:

- Barcelona – Marseille $\Rightarrow$ 164 nm
- Barcelona – Valencia $\Rightarrow$ 185 nm

It was assumed that the ship will navigate at a reduced speed of 10 knots for 1.5 hours when approaching or leaving a port and a berthing / unberthing time of 30 minutes was also considered.

The time spent loading and unloading was considered to be the same as that of the benchmark ship in this route, which is approximately 24 hours in each port of call.

Figure 61 describes the expected operation profile of the ship in the selected route.

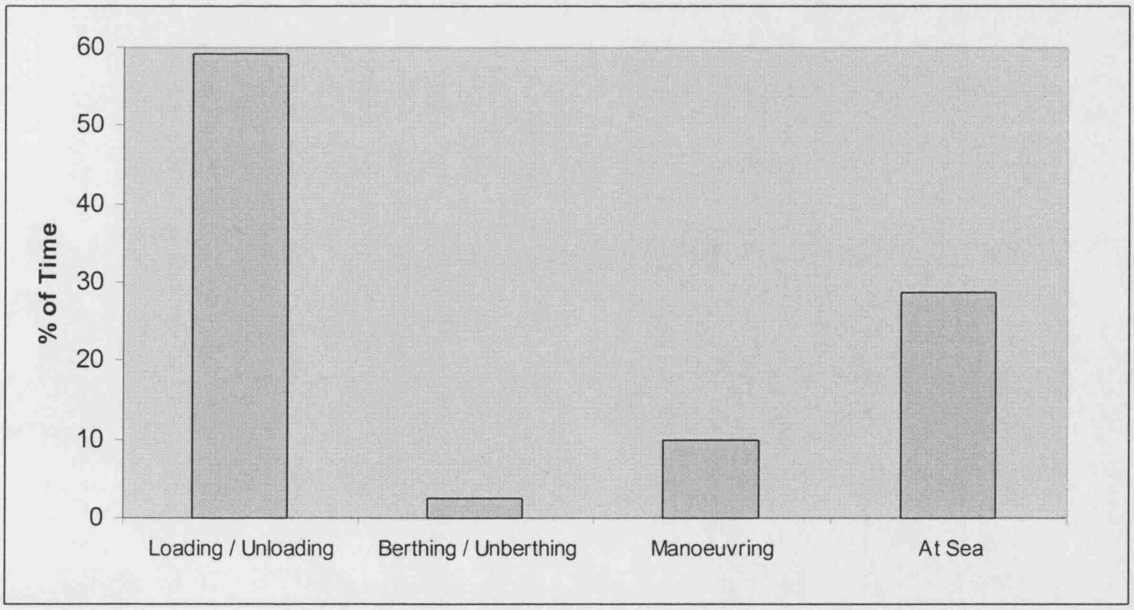


Figure 61 – Operation Profile

8.8 Propulsion System Selection

As discussed in Chapter 5, the options to be considered in the propulsion design of an unmanned ship will be limited to those that achieve a failure rate equal or smaller than the figures expected to be found in the propulsion systems likely to be found on board a conventionally manned ship, as seen in Figure 44.

Having said that, there are still a number of different configurations that must be compared, both economically and in terms of expected performance.

A number of assumptions were made in order to perform a cost comparison of the options available, such as:

- Maintenance cost of a simple cycle gas turbine [67] - £60/hour
- Maintenance cost of an advanced cycle gas turbine [67] - £40/hour
- Maintenance cost of a medium speed diesel engine [67] [72] - £35/hour
- Maintenance cost of a high-speed diesel generator [67] [72] - £40/hour

In order to estimate the cost and performance of an advanced cycle low power gas turbine in the power range required for this ship, the equipment presently being developed by the Warship Support Agency in collaboration with French DGA and industry (Turbomeca) was used.

At present, the development contract has been signed and the project is in the detailed design stage and production units are expected to be available in the 2006 time frame [67]. The engine is a single spool cold end drive machine with a recuperator and a single can external low NOx combustor.

The gas turbine is being rated at 1.8MWe, with the cost being estimated at 80-130% of the equivalent rated high-speed diesel generator, with similar specific fuel consumption [67].

The UPC of the other prime movers considered were estimated from references [95] and [74].

Fuel prices were estimated as £83/ton for IFO 380 used by medium speed diesel engines and as £120/ton for MDO used by gas turbines and high speed diesel engines. The prices were assumed to be as they were in the area of operation at the time this report was made and no attempt was made in forecasting fuel prices trends, since they fluctuate rapidly and randomly, as seen in Figure 62.

The final conclusions, however, would not change when considering fuel prices ranges experienced over the last five years.

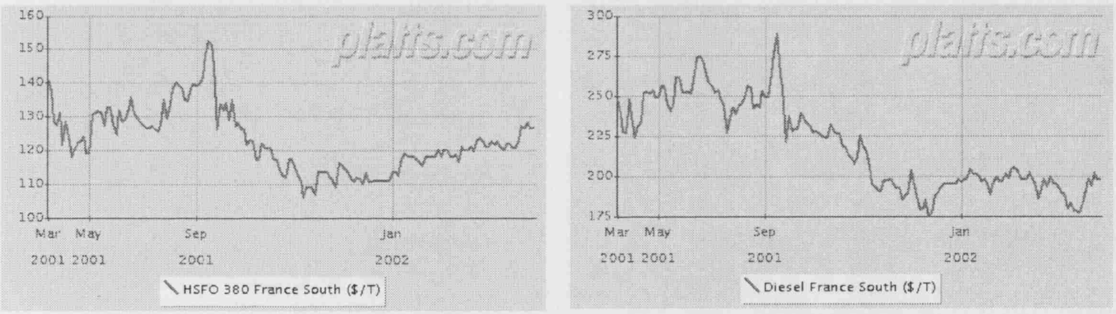


Figure 62 – Fuel Prices Fluctuation [73]

An extra £100k was added to the cost of the manned medium speed arrangement, representing the requirements for extensive seawater and fresh water cooling systems, fuel heating and fuel and lubricating oil conditioning systems [72].

If the need to meet more and more stringent exhaust emission regulations in the future is to be considered, R. R. Simpson [72] suggests an extra 30% increase in the UPC to cater for a Selective Catalytic Reduction (SCR) equipment and 8% in the running cost of the medium speed configuration, covering the cost of increased fuel consumption, spares, catalytic replacement and reducing agent.

Detailed results from the calculations performed for different propulsion configurations achieving a failure rate lower that the benchmark, according to Figure 44, as well as for the benchmark, can be seen in Figure 63.

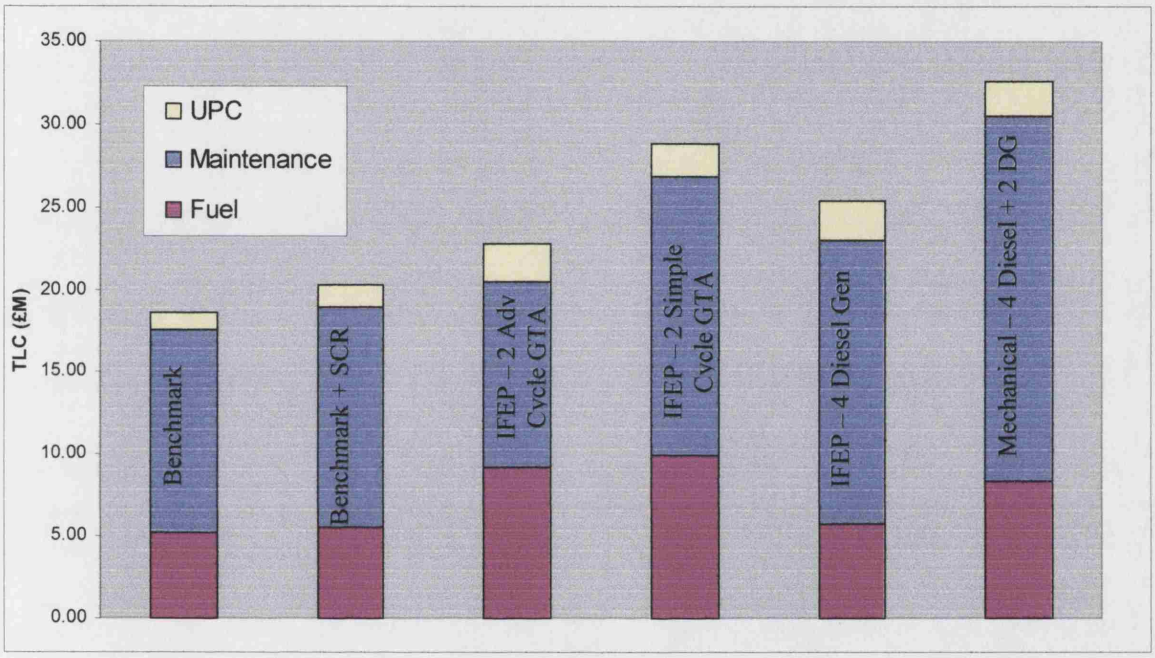


Figure 63 – Through Life Cost of Different Propulsion Options

This figure shows that the obvious choice for the unmanned ship in terms of cost, by a margin of more than 10% over the second best option, is the electrical propulsion using two 1.8MW advanced cycle gas turbines.

Apart from the economical advantages, there are also other characteristics inherent to an electric propulsion configuration that can be advantageous over a conventional mechanical drive.

One of the more important ship design flexibility advantages of an electric drive system results from the alignment-free machinery arrangement. Prime movers can be located remotely from the motor/propeller drive to occupy less critical spaces and to minimise ducting in the case of gas-turbine-powered ships.

Electric reversal capabilities eliminate the need for reversing turbines, reversing gears, or controllable pitch propellers. Dynamic braking from high speeds is achievable with energy dissipation in electric resistors, providing protection for prime movers overspeed.

The choice of gas turbines as prime movers also presents some advantages over diesel engines. Apart from the lower failure rate, the space and weight savings achieved by a gas turbine arrangement, which requires fewer supporting systems when compared with diesel engines, can compensate for the larger volume required in an electric propulsion configuration.

8.9 Auxiliary Systems

With the objective of reducing the number of auxiliary equipment on board, and considering the route selected and the high-quality fuel to be supplied to the vessel, as required for the gas turbines, it was possible to design a fuel system comprising a small volume fuel tank, with capacity for one return trip from any of the ports where the vessel is to operate, estimated as 14 m^3, plus margins.

Since a normal leg will take only around 16 hours, including transit and manoeuvring time, the tank would act as a conventional service tank (that has to have a capacity for at least eight hour's operation at sea [79]) and fuel treatment systems such as settling tanks or centrifuges become unnecessary.

The operational profile of the vessel, with at least 24 hours in every port of call, would be more than enough for bunkering operations, especially when the volume of fuel involved is considered.

Electrification of other auxiliary systems, such as starting air compressors and pumps was made possible by the selection of an electric propulsion configuration, eliminating hydraulic and pneumatic lines throughout the vessel

8.10 Propulsor Selection

The following propulsor options were investigated:

- Fixed Pitch Propeller (FPP);
- Controllable Pitch Propeller (CPP);
- Water Jets;
- Pods

Considerations on cost, internal volume, weight, risk, efficiency over power range and ARM were made as listed in Table 13 and it became clear that the dispute would be between FPP and pods and a more detailed analysis was performed.

	Weighting	Propeller FPP	Propeller CPP	Water Jet	Azimuth Pods
UPC	2	5	4	3	2
Internal volume	2	3	3	2	5
Weight	1	4	4	3	4
Risk	3	5	4	3	2
Efficiency	4	3	4	3	4
Manoeuvrability	5	3	4	4	5
Reliability	5	5	3	3	3
Maintainability	5	4	3	2	5
Total Score		107	96	79	105

Table 13 – Propulsor Selection Matrix

Difference in material costs consists of replacing propulsion motors, shafts, bearings, sealings, propellers, castings of the bosses and the shaft supporters, rudders and their machinery with pod units and their turning, cooling and power supply appliances. The material costs of the podded drive can be 19% higher than the costs of the material that they replaced [75].

In standard shaft line arrangements, producing and transferring electrical power from generator to the propulsion motor shaft is approximately 1,5% more efficient than in pods, since the diameter of the propulsion motor in pod is normally reduced in order to gain good hydrodynamic efficiency. On the other hand, transferring mechanical power from the propulsion motor to the propeller shaft is approximately 1,5% more efficient in case of podded drive. Therefore shaft line and podded drive can be regarded equal when comparing the power transferring efficiency [75].

According to some sea trial results, podded drive would reduce fuel consumption in 5%, due to an increase in propeller efficiency attributed to a "cleaner flow" viewed from the blades.

These percentages and the fuel cost expected in 25 years, as already given in Figure 63, indicate a significant difference in the though life cost of a podded drive and a standard shaft line transmission when applied to the unmanned ship.

This economical advantage is increased, since the use of a pod eliminate the need of a stern thruster required by the automatic berthing system defined in Chapter 4.

It is obvious that the pod arrangement saves internal space once taken by the propulsion motors, but it is important to note that this saving is concentrated in lower decks but on the deck above the pod unit it consumes more deck area than it saves. The steering room compartment is replaced with rooms containing turning, cooling, and power supply appliances. These appliances require more than twice the space of a regular steering room.

From the facts listed above, the propulsor of choice was a pod rated at 3MW.

At the time this report was prepared, the only COTS pod propulsion system available at the low power required was the ABB "Compact Azipod@", covering the range from 400 kW to 5 MW.

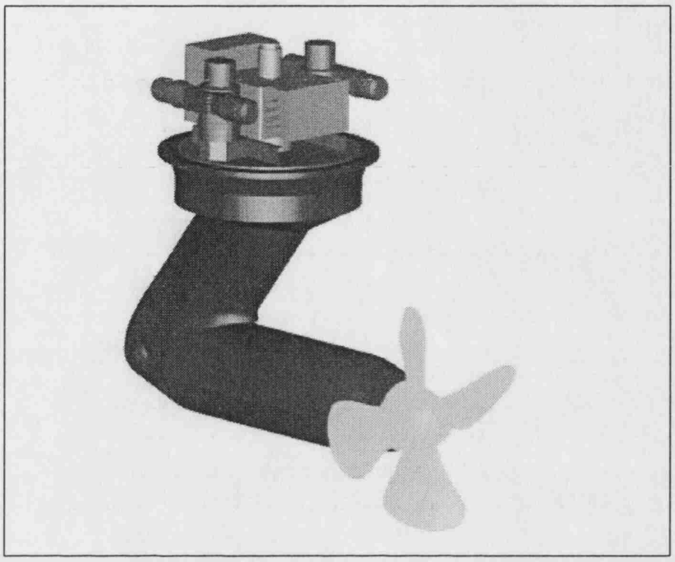


Figure 64 – ABB Compact Azipod@ [76]

The Compact Azipod@ incorporates a permanent magnet synchronous motor, operating at 660V, with a fixed-pitch propeller that is mounted directly onto the motor shaft. By using permanent magnet technology, the outer diameter of the pod could be decreased, which improved hydrodynamic efficiency. The uniform frame design enables the motor to be directly cooled via convection to the surrounding seawater without using any additional cooling media [76].

8.11 Electric Drive

The speed (rpm) of the Azipod propulsion motor is controlled by the ACS 600 Marine Drive W, which has features as follows: water cooling, low voltage (525 to 690V), and full nominal torque from zero speed to the maximum propeller speed in both rotation directions.

The system consists of an AC drive control where inverter switching directly controls flux and torque of the motor.

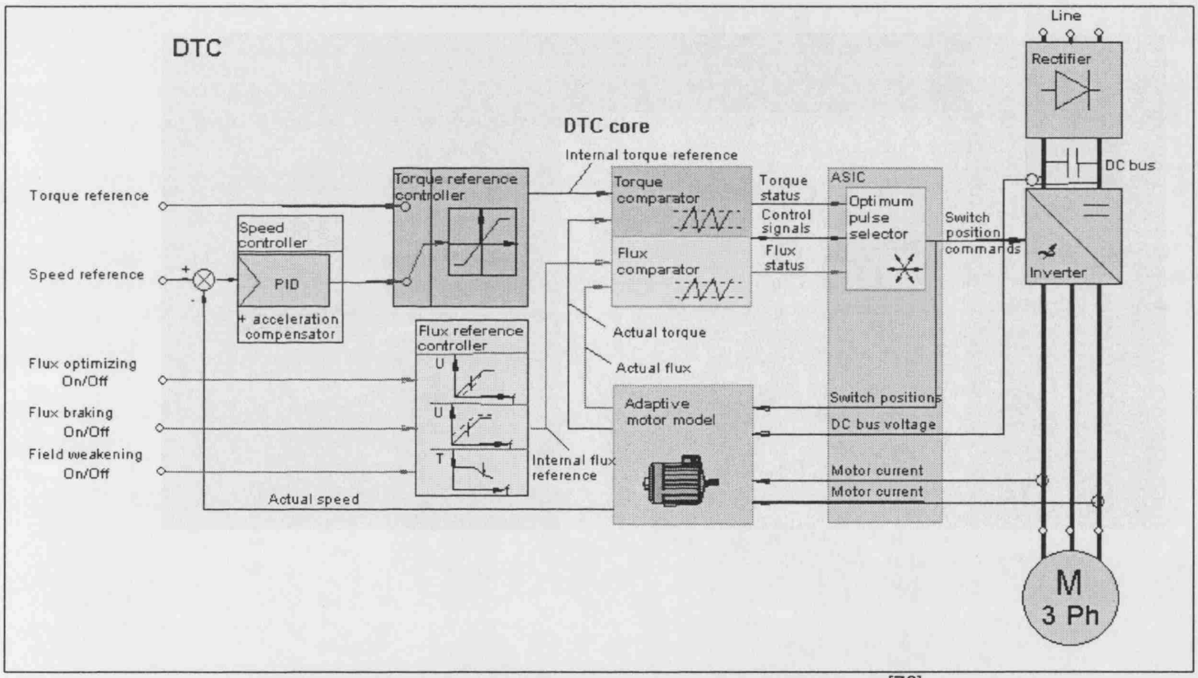


Figure 65 – Direct Torque Control Diagram [76]

The measured motor current and voltage are inputs to an adaptive motor model, which produces an exact actual value of flux, and torque every 25 microseconds.

Motor torque and flux two-level comparators compare the actual values to the reference values produced by torque and flux reference controllers and depending on the outputs from the controllers, the optimum pulse selector determines the optimum inverter switch positions.

The inverter switch positions again determine the motor voltage and current, which in turn influence the motor torque and flux and the control loop is closed as represented in Figure 65 [76].

8.12 Busbar Voltage Selection

The fault current levels were calculated for different voltage levels, as detailed in Annex 14 and the results were plotted in Figure 66.

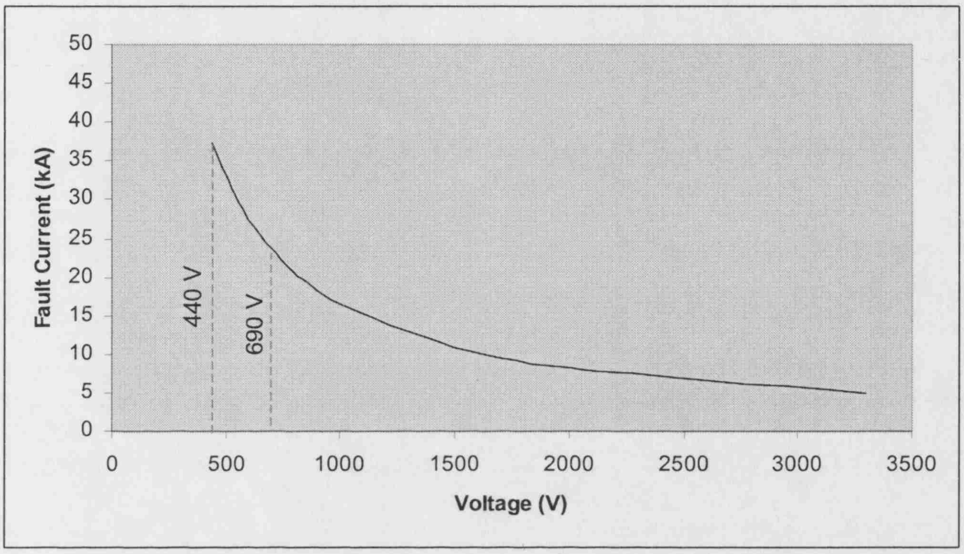


Figure 66 – Fault Current Levels for Different Voltages

Although it would be possible to use a 440V busbar both for propulsion and for domestic loads, given the COTS breaking capacity currently available, a 690V propulsion busbar was selected, since it is the required supply voltage for the ACS 600 Marine Drive W.

Since Classification Societies rules [79] limits the voltage in the domestic busbar to 500V, arrangements to transform the 690V from the propulsion busbar to the standard 440V required for the ship services busbar will be required.

8.13 Quality of Power Supply

Classification Societies rules [79] stipulates minimum standards that main ships services electrical supply must comply with, such as:

- THD[16] of the voltage waveform at any switchboard < 8%

Calculations of harmonic penetration in the service busbar, detailed in Annex 15 showed that a THD of 10% is expected, requiring a harmonic filter to be incorporated in the system.

Finally, the possible solutions available to transform the 690V from the propulsion busbar to the required 440V for the ship services busbar were:

- Transformers;
- Motor-generator sets (MG sets);
- Static converters.

MG sets have the advantage of providing a clean supply, even when harmonics vary as a function of the load, but are heavy, have an efficiency of around 92% and demands more maintenance than the other options.

Static converters can be lighter but more expensive, with efficiencies in the order of 95% - 97%.

Transformers, on the other hand, have efficiencies greater than 99% and very reduced maintenance requirements, but will require some harmonic filtering, as already mentioned.

[16] Total Harmonic Distortion

The extremely high reliability and simplicity of construction of transformers when compared with the other options, however, were the decisive factors leading to its selection for the proposed system, converting the 690V from the propulsion busbar to 440V.

8.14 General Arrangement

With the definition of the main equipment throughout this Chapter and operation philosophies, as discussed in the previous Chapters, it is possible to produce a General Arrangement for the unmanned ship, as seen in Annex 17 to 21.

The following factors were taken into consideration:

a) Equipment posing higher fire risks, such as prime movers, fuel systems, electric drives and switchboards were segregated from other systems, creating a zone that will operate in a "closed down" configuration, as explained in Chapter 7;

b) The fuel tank, due to the small volume, was located above the level of the main users, eliminating the need of fuel transfer pumps;

c) Redundant equipment were located as separated as possible from each other, while facilitating their cross-connection capabilities;

d) Two control centres were fitted on board, with the main one located in the main mast structure with an emergency backup located in the forecastle, near the emergency generator;

e) Communication antennas were also duplicated in the forward mast, as a backup system for those located in the main mast;

f) A “double hull” configuration was used throughout the extension of the cargo holds, increasing the survivability of the ship in case of collision;

g) Extra spaces made available by removing the superstructure and by exploiting the flexibility of the electric propulsion was used as additional cargo spaces;

h) Removal routes for main equipment, such as gas turbine alternators, were made as easy as possible, with little or no impact on other equipment in the vicinity;

8.15 Stability

Among other differences between the unmanned ship and the Conofeeder 300, the removal of the superstructure and the crew related equipment, allied with the substitution of the medium speed diesel engine propulsion system by a much lighter arrangement using gas turbines, had a significant effect on the displacement and on the vertical and longitudinal position of the centre of gravity.

A comparison between the stability characteristics and the trim obtained for both the unmanned ship and our benchmark (Conofeeder 300) was performed for the following situations:

a) Ballast Condition

Although stability is not a problem in this situation, the weight of the superstructure and the engine room concentrated in the rear ¼ portion of the hull requires around 900 ton of ballast water to achieve a 2.0 metre trim.

In the same condition, the unmanned ship would only require 700 ton of ballast water

b) Containers Homogeneously Loaded to 14 ton

In this situation, due to stability limitations, the Conofeeder 300 has a design capacity of 190 TEU.

In order to ensure that the same assumptions and safety factors were taken into account, the unmanned ship capacity for the same loading condition was estimated using the following procedure:

- The KG of the Conofeeder 300 when loaded with 190 TEU weighing 2660 ton in total was assumed as the maximum allowable for this condition;

- By adding and subtracting equipment, the unmanned ship KG was estimated;

- Cargo was added until the limits of the stability criteria were reached.

As a result, the unmanned ship would be able to transport 202 TEU homogeneously loaded to 14 ton.

c) Maximum TEU capacity

The Conofeeder 300 was designed to carry a maximum of 301 TEU arranged in order to comply with the stability criteria and to reach the maximum draft of 4.88m.

The same procedure detailed in the previous section was used and it was possible to accommodate 321 TEU onboard the unmanned ship.

8.16 Structure

Bending moments and shear stresses were calculated for different loading conditions in order to evaluate the need of a different structural arrangement for the unmanned ship.

The results for the worst case studied can be seen in Figure 67 and it becomes clear that the loads applied to the unmanned ship are smaller throughout the length of the vessel.

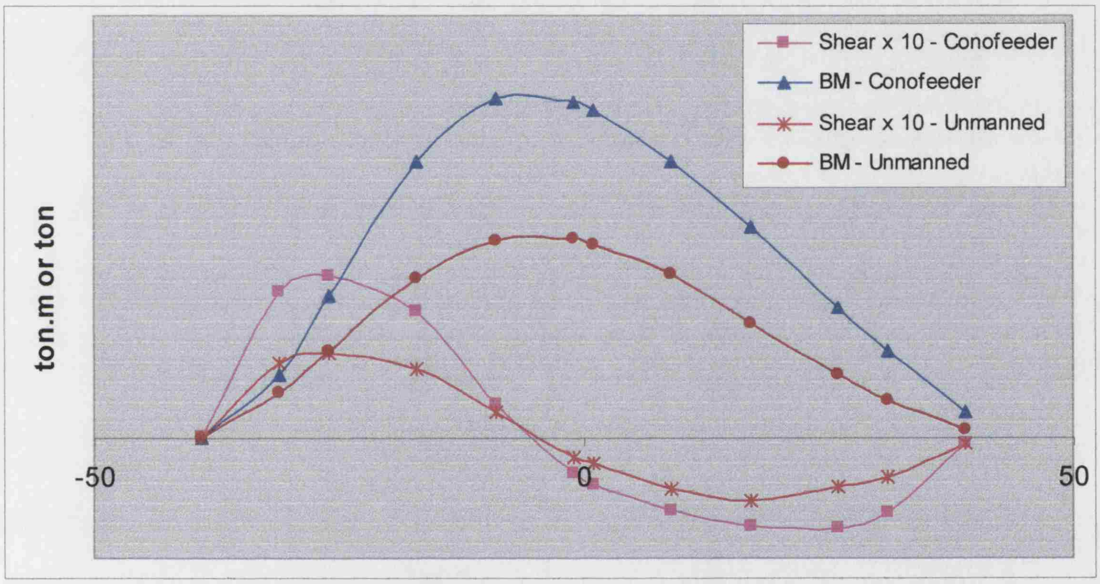


Figure 67 – Shear Force and Bending Moment Distribution

There is the need of different local structural arrangement, such as in the area around the pod propulsor, but no major difficulty is foreseen.

8.17 Summary

In this chapter, an unmanned ship design was developed for a selected route, using a state-of-the-art vessel as a benchmark.

The main differences between both designs are:

- The propulsion plant selected for the unmanned ship consists in an electric propulsion configuration, based on two identical advanced cycle gas turbines and a pod propulsor, in contrast with the benchmark configuration that uses a traditional mechanical propulsion system, based on one medium speed diesel engine driving one controllable pitch propeller through a gearbox, which result in the following main differences:

    - The unmanned ship propulsion plant has a lower expected failure rate when compared with the benchmark;

    - The selected propulsion system has a through life cost 11% higher than the benchmark;

    - An extra cargo hold with a capacity of 6 TEU was made available due to the layout flexibility provided by the electric propulsion configuration;

    - The use of a pod propulsor allied with bow thrusters provide the unmanned ship with high manoeuvrability even at low speeds, which is essential for the automatic berthing system proposed in chapter 5;

- Fuel treatment systems and fuel transfer pumps were eliminated by adopting an operational concept where small fuel tanks, located above the level of the main users, are used with more frequent bunkering operations;

- The elimination of the crew-related spaces in the superstructure provided extra cargo spaces with a capacity of 16 TEU;

- Stability calculations demonstrate that the unmanned ship would have a TEU capacity approximately 6.5% higher than the benchmark either in the standard "containers homogeneously loaded to 14 tons" condition or in the "maximum TEU capacity" condition;

- Structural calculations demonstrate that the unmanned ship will experience smaller bending moments and shear forces throughout the length of the vessel than those calculated for the benchmark in any equivalent loading condition.

CHAPTER 9

ECONOMIC ANALYSIS

9.1 Introduction

In the previous chapters, an engineering assessment has been undertaken in key automated systems and their operation philosophies needed in a ship's design to eliminate the crew in the main areas of navigation, propulsion and damage control.

As expected, a suitable fully automated system capable of performing the different tasks involved in the operation of a merchant ship would require the introduction of extra redundancy or new technologies that would increase the initial overall cost of the vessel.

In this Chapter, the building cost difference between the proposed unmanned ship and the selected benchmark will be estimated, as well as the through life cost of both ships.

As a result, the economic viability of the unmanned ship will be assessed by comparing the required freight rate of both configurations over a range of assumed parameters.

9.2 Initial Cost

The use of algorithms or models commonly used to estimate the cost of a vessel [95][59] may only apply to the groups where the differences between the unmanned ship and a conventional ship are not accentuated, such as the steelwork.

For the other main groups – machinery and outfit – information from manufacturers or estimation based on similar equipment were used and the costs were added or subtracted from the total cost of a conventional containership.

The world shipbuilding market is characterised by a strong imbalance of supply and demand and over-expansion of shipbuilding capacity in Far East countries, especially Korea, has led to very low offer prices in most market segments.

Newbuilding price developments are presented in Figure 68 in the form of an index, with the price level of 1987 equalling an index of 100.

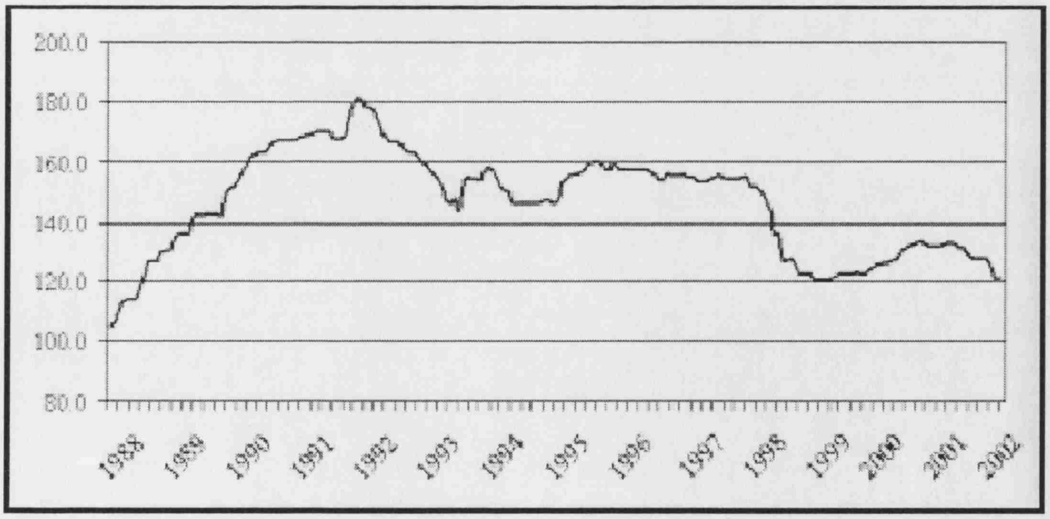


Figure 68 – Newbuilding Price Developments [88]

Price developments in the last 20 years do not follow a clear trend and did not keep pace with inflation rates, being very sensitive to the economic situation of the major shipping and shipbuilding nations.

The graph clearly shows the significant drop in prices following the Asian economic crisis of 1997/98, as an example, and indicates that 2002 price levels are only 20% higher than they were in 1987.

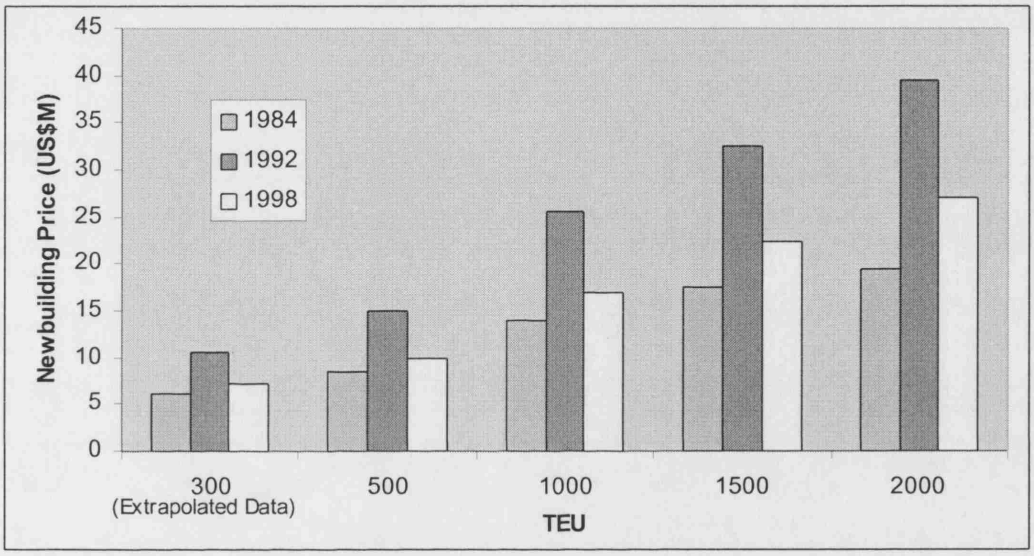


Figure 69 – Containership Newbuilding Prices Evolution [8]

The cost of a new conventional 300 TEU containership was then estimated and extrapolated from actual data [8][88], as shown in Figure 69 and corrected using Figure 68, being considered as £5M.

Major equipment added or removed from the benchmark ship, as discussed in the previous chapters, can then be listed with the assumed cost and the initial cost of the unmanned ship can be calculated, as shown in Table 14.

Item	Cost (£k)	Sources
Benchmark Ship	5,000	Figure 69 and Figure 68
Crew-Related Items	- 1,500	Figure 10
Propulsion Plant (diff)	+ 930	Figure 63
Propulsor (diff)	+100	Refs [95] and [75]
Mooring System (diff)	+ 200	Mooring Systems Ltd
Fire Inhibition	+ 360	Est. from similar equipment
Navigation / Comm.	+ 50	Est. from similar equipment
ETA	+ 80	Est. from similar equipment
Total	**5,220**	

Table 14 – Unmanned Ship Initial Cost

It is important to note that the costs listed above already consider any investments ashore, which is the case of the mooring and navigation systems.

9.3 Operating Costs

The main sources of differences between the unmanned ship and the benchmark regarding operating costs will be generated by the following factors:

- Highest fuel consumption of the gas turbines used on board the unmanned ship;
- Use of marine diesel oil by the gas turbines;
- Maintenance costs;
- Different TEU capacities;
- Highest electric load due to the controlled atmosphere required by the fire inhibition system; and
- Elimination of crew costs.

The most important factors are those related with fuel and crew costs, since the lower maintenance cost of the propulsion plant selected for the unmanned ship would counterbalance any foreseen increase in the maintenance load due to the incorporation of extra equipment in the design.

These factors were already discussed in the previous chapters and Table 15 is a summary of the major differences for both vessels when operating in the selected route:

Item	Cost / year (£k)	
	Conventional	Unmanned
Fuel	209	397
Crew	274	0
Total	483	397

Table 15 – Operating Cost Comparison

9.4 Required Freight Rate Comparison

A spreadsheet developed by Fellows [89] was used to estimate the required freight rate for both the unmanned ship and the benchmark, when operating in the selected route and the results are summarised in Figure 70.

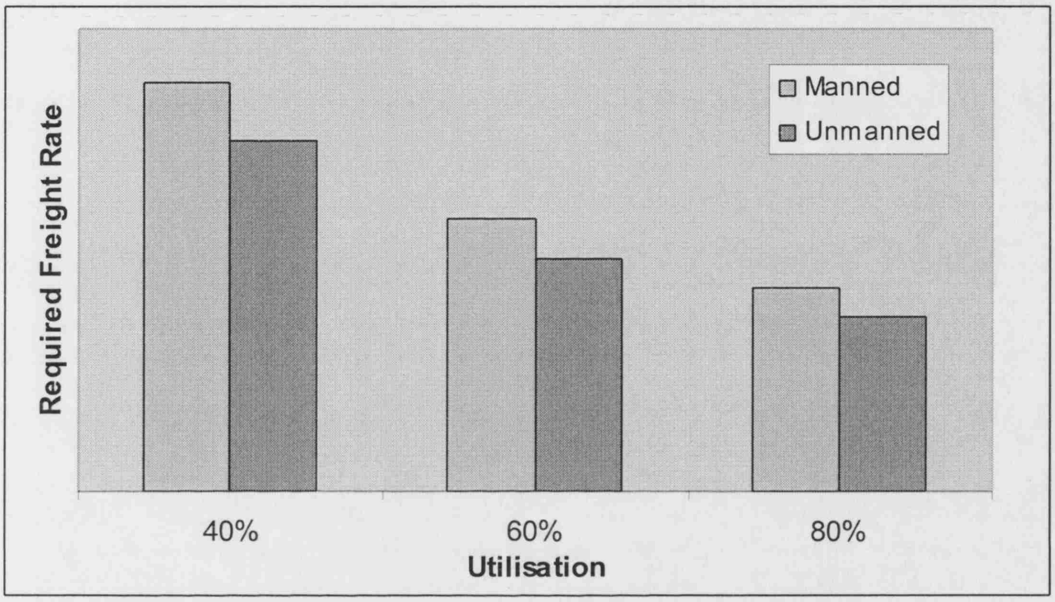


Figure 70 – Required Freight Rate Comparison

Port charges were estimated from a number of references [95][71] and the software was used to compare required freight rates for a range of utilisation factors, resulting in a 14% difference in favour of the unmanned ship.

Increased insurance premiums were considered for the unmanned ship, since it is a brand new concept, and other parameters such as required rate of return, depreciation of capital asset, build period, loan characteristics, inflation and interest rates were kept constant for both concepts in the analysis.

It becomes clear that the economic advantages of the unmanned ship concept are very significant when applied to the case study presented in this thesis.

9.5 Summary

As far as economic issues are concerned, the following conclusions can be drawn from the analysis presented in this chapter:

- The elimination of crew-related items reduced the impact of the introduction of extra redundancy and new technologies into the design of the unmanned ship, resulting in an increase of the initial overall cost of the vessel of less than 4% when compared with the benchmark ship;

- As far as operating costs are concerned, crew and fuel are the main items responsible for the cost difference between the unmanned ship and the benchmark when operating in the selected route, resulting in a difference of 18% in favour of the unmanned ship;

- An estimate of the required freight rate for both design concepts when operating in the selected route demonstrated that the unmanned ship is the most profitable concept, irrespective of the utilisation factor assumed.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

Through the development of this work, a new concept in maritime transportation has been proposed.

This concept appears to be an attractive solution to the maritime manpower shortage forecasted to the near future, especially considering that the unmanned ship can, in some cases, be more profitable than a successful state-of-the-art conventional ship.

In order to prove the feasibility of the concept, a complete ship design was presented and a direct comparison could be made with current maritime practice.

The main technological challenges have been addressed and the solutions proposed are based exclusively on well-proven technology or on services expected to be commercially available and fully operational in the next six years, integrated in a system capable of performing all the tasks required during the operation of a merchant ship.

Initially, a complete autonomous navigation system was proposed with the following characteristics:

- Company pre-approved passage plans will be used, following a practice adopted by some ship owners, and will define “lanes” of different widths for every phase of the journey, minimum clearances from other ships for both COLREG-based collision avoidance and emergency manoeuvre and speed limitations;

- Independent satellite positioning systems will be used as the main position fixing equipment, with an hyperbolic navigation system as a backup;

- The integration of ARPA and AIS, together with the precise position fixing system and the information contained in the company approved route plan will provide the data required for collision avoidance calculations;

- Routeing systems will be defined for the unmanned ship in order to further reduce the probability of a collision with small boats and sailing vessels;

- Weather routing services will be used to keep clear of rough weather areas and pitch and roll sensors will provide information needed to avoid excessive motion and stress;

- Information gathered from Notice to Mariners and other safety broadcasts will be analysed by the ship control centre ashore and the passage plan will be updated and uploaded to the vessel, if necessary;

- Vessel Traffic Services can play an important role providing remote pilotage services and broadcasting the position of all vessels in their jurisdictional area, especially small boats with poor radar cross section.

On the initial and final phases of any journey, the requirement for extremely precise position determination demanded by berthing operations is fulfilled by real-time kinematic (RTK) satellite positioning systems.

With the philosophy of providing a backup system for every technology used, a line-of-sight high-speed data link with real time video transmission was selected in order to enable the remote control of the vessel in berthing operations.

Finally, mooring operations can be performed without boarding the unmanned ship by using advanced mooring systems based on vacuum technology.

In terms of propulsion, the main objective was to design an unmanned system that would present a probability of total propulsion loss below the figures expected from a conventionally manned plant, at a minimum cost.

The main characteristics of the proposed system are as follows:

- The selection of an electric propulsion configuration with only two prime movers (gas turbines) made it possible to achieve the same number of total propulsion losses per million hours when compared with a conventionally manned plant with a medium speed diesel plus two diesel generators configuration;

- Due to the operation profile of the vessel, allied to the use of marine diesel oil for the gas turbines, the fuel system was extremely simplified, reducing the likelihood of failures;

- The similarities of the operation profile of the designed ship and of a commercial long-haul aeroplane became evident and the aviation industry maintenance philosophy was adopted.

Communication with other ships and shore facilities was also discussed and the selected system make use of the technology employed in naval fleets when a vessel is used to automatically relay messages received in one frequency through other frequency.

This system will integrate the unmanned ship into the communication structure now in use at sea, allowing among other things, bridge-to-bridge-like communications, where VHF signals transmitted by one ship can be relayed to the ship control centre via satellite or HF and vice versa.

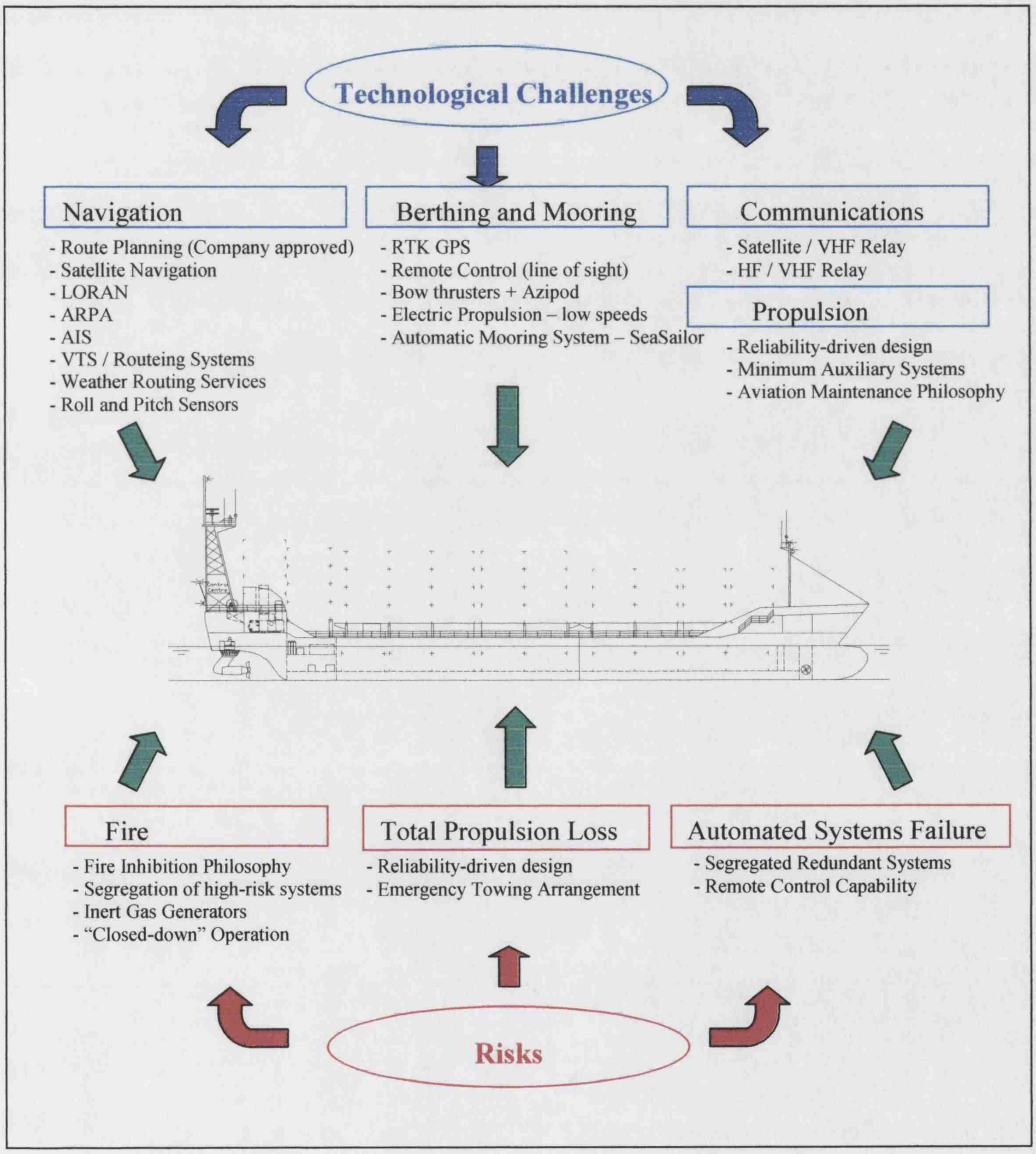


Figure 71 – Main Factors Considered in the Design

Some risks inherent to the operation of a ship without a crew on board were also taken into consideration and some solutions have been proposed.

Small fires, easily put out by the crew in a conventional vessel, could pose a unacceptable risk in an unmanned ship and it was decided that a fire inhibition concept would be implemented, where equipment or systems posing a greater fire risk would be segregated in an airtight zone flooded with inert gas.

The possibility of a total loss of propulsion or complete system failure was also considered and an emergency towing arrangement was fitted in the ship, allowing the vessel to be towed without the need to board it.

Finally, the failure of the automated systems is also a possibility and a remote control capability, to be used in an interventionist mode, was included in the design.

A representation of the main technological challenges and safety concerns considered in the unmanned ship design can be seen in Figure 71

The complete unmanned ship system, taking into account the present trends experienced by the maritime industry, was designed to cause little or no impact on well established procedures in use at sea or on port facilities, integrating and interacting with other components of the maritime transportation system.

The exchange of information between the unmanned ship and other elements is summarised in Figure 72, where the integration and interaction with the maritime system can be visualised.

An economic analysis was then performed for the operation in the selected route and the profitability of the unmanned ship concept was demonstrated.

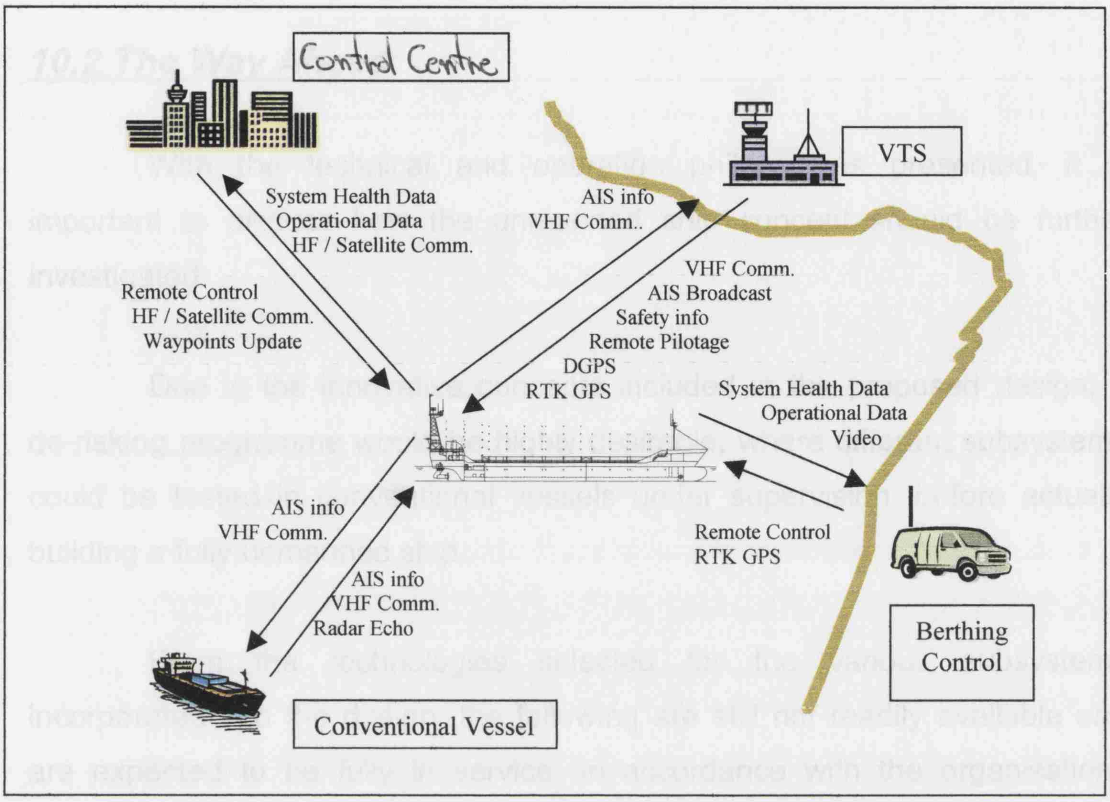


Figure 72 – Integration and Interaction with the Maritime System

The impact of the investment needed to incorporate new technologies and extra redundancy into the unmanned ship design was significantly reduced by the elimination of crew-related items, resulting in an increase of only 4% of the initial cost of the vessel, when compared with the benchmark.

On the other hand, the significant reduction of the operating costs, when compared with the manned benchmark, results in a 14% reduction of the required freight rate for the unmanned ship concept.

With this analysis, it was demonstrated that the concept of an unmanned ship is not only technically possible but can also be very attractive as far as profitability is concerned.

10.2 The Way Ahead

With the technical and operation philosophies presented, it is important to discuss how the unmanned ship concept should be further investigated.

Due to the innovative concepts included in the proposed design, a de-risking programme would be highly desirable, where different subsystems could be tested in conventional vessels under supervision, before actually building a fully unmanned ship.

From the technologies selected for the various subsystems incorporated into the design, the following are still not readily available and are expected to be fully in service, in accordance with the organisations responsible for them, by the dates mentioned:

System	**Fully in Service**
GALILEO satellite navigation system	2008 (start in 2006)
Automatic Identification System (AIS)	2008 (start in 2002)
Advanced Cycle Low Power Gas Turbine	2006
Teledesic (Global Broadband Communication)	2006

The de-risking process, however, can be started today with the remaining systems not affected by the services mentioned above.

In many cases, this process would consist only in the integration of equipment and systems already available on board in order to form the new unmanned systems proposed throughout this thesis.

Especially considering the predicted profitability of the concept, there is no reason to doubt that the first fully automated unmanned ship could be in service in the present decade.

REFERENCES

[1] "ISF/BIMCO 2000 Manpower Update – The World-wide Demand for and Supply of Seafarers" – International Shipping Federation – April 2000

[2] "Communication from the Commission to the Council and the European Parliament on the Training and Recruiting of Seafarers" – Commission of the European Communities – Brussels – April 2001

[3] IMO News – Issue 1 – International Maritime Organisation – 2001

[4] International Maritime Organisation (IMO) website – www.imo.org

[5] Murayama Y. et al. – "A Study on Seafarers' Work-load " – Journal of the Japan Institute of Navigation – 1995

[6] "ITF Uniform "TCC" Collective Agreement for Crews on Flag of Convenience Ships" – International Transport Workers' Federation – January 2001

[7] "Ship Costs in the 1990's – The Economics of Ship Operation and Ownership" – Drewry Shipping Consultants – London – 1994

[8] "Ship Costs – Issues, Developments and Prospects to 2003 – Drewry Shipping Consultants – London – 2000

[9] F. B. Ditizio et alli – "Autonomic Ship Concept" – Naval Engineers Journal – September 1995

[10] "Effective Manning of the US Merchant Fleet" – Committee on Effective Manning, National Research Council, National Academy Press, Washington, D.C. 1984

[11] Martha Grabowski – "Distributed Intelligent Navigation Systems" – Intelligent Ships, Intelligent Ports Symposium – Hamburg – 1999

[12] Richard B. Langley – "RTK GPS" – University of New Brunswick – USA – 1998

[13] "1999 Federal Radionavigation Plan (FRP)" – U. S. Department of Transportation and U. S. Department of Defence – USA – 2000

[14] "GPS Error Sources" – www.gnss.f2s.com

[15] "GPS Selective Availability Discontinued" – National Geodetic Survey – USA – http://www.ngs.noaa.gov

[16] "Global Positioning System Standard Positioning Service Performance Standard" – Assistant Secretary of Defense for Command, Control, Communications and Intelligence – Washington – USA – October 2001

[17] Jörgen Börjesson – "GLONASS Contributions to Space Geodesy" – Technical Report No. 366L – Chalmers University of Technology – Sweden – 2000

[18] Jörgen Börjesson, Jan Johansson and Fredrik Darin – "GLONASS: experiences from the first global campaign" – Karlskrona – Sweden – 1999

[19] "Galileo Mission High Level Definition" – European Commission – Doc. EMRF 5/5/2 – April 2001

[20] Novatel website – www.novatel.com

[21] Chris Rizos & Shaowei Han – "Status and Trends for High Precision GPS Kinematic Positioning" – 1998

[22] Thales Navigation Website – www.thales-navigation.com

[23] Ashtech Website – www.ashtech.com

[24] S. Ryan, M. Petovello, and G. Lachapelle – "Augmentation of GPS for Ship Navigation in Constricted Water Ways" – The Proceedings of the ION National Technical Meeting – USA – 1998

[25] S. Ryan and G. Lachapelle – "Impact of GPS/Galileo Integration on Marine Navigation" – Proceedings of ION AM 2000 – USA – 2000

[26] "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System – Final Report" – John A. Volpe National Transportation Systems Center – USA – August 2001

[27] K. D. McDonald – "Performance Improvements to GPS in the Decade 2000 – 2010" – Proceedings of the 55th Annual Meeting of the Institute of Navigation – USA – 1999

[28] Edwin L. Key – "Techniques to Counter GPS Spoofing" – MITRE Corporation – 1995

[29] Eurofix website – http://www.eurofix.tudelft.nl

[30] G. Linn Roth – "The Case for Loran" – International Loran Association – 1998

[31] "System Specification for the Ports and Waterways Safety System" – Vessel Traffic Services Project Office – U. S. coast Guard – 1997

[32] Mami Ueno – "A GPS-based System for Precise Shipping Guidance and Control" – Journal of Marine Science and Technology – Vol. 5 No 1 – 2000

[33] Burleigh Marine Systems Ltd – www.naval-technology.com /contractors/fenders/dun/

[34] Riegl Website – http://www.riegl.co.at/appl_notes/e_ia045.htm

[35] Harbour Marine Website – www.harbour-marine.com.au /jetty/smartdock.html

[36] Young C. Lee and Daniel G. O'Laughlin – "A Performance Analysis of a Tightly Coupled GPS/Inertial System for Two Integrity Monitoring Methods" – MITRE Corporation – 1999

[37] O. S. Salychev et alli – "Low Cost INS/GPS Integration: Concepts and Testing" – Institute of Navigation Technical Meeting – USA – 2000

[38] Canadian Coast Guard Website – http://www.tc.gc.ca/cmac/ documents/AIS_Ehtm.htm – October 2000

[39] United States Coast Guard Website – www.navcen.uscg.gov

[40] "Recommendation on Performance Standards for Universal Automatic Identification System (AIS)" – Resolution MSC.74 (69) – International Maritime Organisation – 1998

[41] Fred W. Pot – "Recommendations for Integration of AIS in Bridge Operations" – Marine Management Consulting – USA – 2000

[42] Universal Automatic Identification System Website – www.uais.org

[43] "AIS at last?" – COMPUSHIP – June/July 2000

[44] Sam Mead & David Edmonds – "Passage Planning Made Efficient and Cost Effective" –

[45] WNI Oceanroutes Website – www.oceanroutes.com

[46] AppliedWeather Website – www.appliedweather.com

[47] IMO Secretary General Speech – VTS 2000 Symposium – Singapore – 2000

[48] IMO Secretary General Speech – International Maritime Pilots' Association – USA – 2000

[49] Tanktech Co. Ltd Website – www.tanktech.co.kr

[50] Litef GmbH – Naval Navigation Products Group Website – www.litef.com

[51] "Liner Shipping Outlook for the Port at Quonset Point" – Rhode Island Economic Development Corporation – USA – 2000

[52] "Time's up for Ageing Boxships" – Containerisation International – June 2001

[53] Booz Allen & Hamilton – "Feasibility of Study of Hub Port Development" – 1997

[54] Conoship International Website – www.conoship.com

[55] Alphaliner Website – www.alphaliner.com

[56] "Naval Architecture Containership Design Exercise – Procedure" – Version IV – University College London – October 2001

[57] International Transport Workers' Federation website – www.itf.org.uk

[58] M. Gertler – "A Re-analysis of the Original Test Data for the Taylor Standard Series" – DTMB – 1954

[59] D.G.M. Watson & A.W.S. Gilfillan – "Some Ship Design Methods" – RINA – 1976

[60] "User Guide for HULLPAK" – University College London – 2000

[61] "Significant Ships" – Royal Institute of Naval Architects – RINA – 1995 – 2000

[62] "International Convention on Load Lines" – International Maritime Organisation – London – 1966

[63] Søren Abildsten Bøgh – "Reliability and Safety of All Electric Ships" – LOGIMATIC A/S – 1999

[64] I. Ahlqvist – "Increasing Availability Through Introduction of Redundancy" – Electric Propulsion: The Effective Solution? – IMarE – 1995

[65] A. L. Pineiro – "The BASFEM Project: An Academic Approach to a Reliability Data Base of Ship Electrical Components" – ICMES – ImarE – 1993

[66] John P. Bentley – "An Introduction to Reliability and Quality Engineering" – Longman Scientific and Technical – UK – 1993

[67] Warship Support Agency – Defence Logistics Organisation – Marine Propulsion Systems IPT

[68] M. Driscoll et alli – "LM2500 Failure Review Board Efforts Lead to Reliability Improvements" – http://www.dt.navy.mil/pao/excerpts%20pages/2000/lm2500Sept.html

[69] Diretoria de Engenharia Naval – DEN

[70] Marc Calabrese – "Improved LM2500 Gas Turbine Engines" – Wavelengths – June 2001

[71] "Fairplay Ports Guide" – Vol. 4 – Fairplay Publications Ltd – 1999 – 2000

[72] R. R. Simpson – "Gas Turbine Powered Containership" – IMarE – 1995

[73] www.platts.com

[74] www.gas-turbines.com

[75] "Summary Report 1999" - Kvaerner, ABB and Wärtsilä NSD – Det Norske Veritas – 1999

[76] www.abb.com

[77] "NES 532 – Guide to the Design of Electrical Supply and Distribution Systems in Surface Vessels" – UK MoD – 1995

[78] "Future Operational Constraints of Switchboards" – J. P. Sorrel – AES Proceedings – 1997

[79] "Rules and Regulations for the Classification of Ships" – Lloyd's Register of Shipping – 2000

[80] QinetiQ AAV Demonstration – Oceanology International 2002 – London – UK

[81] QinetiQ website – www.qinetiq.com

[82] Mooring Systems Limited website – www.mooring.co.nz

[83] U.S. Congress, Office of Technology Assessment – "Marine Applications for Fuel Cell Technology" – U.S. Government Printing Office – February – 1986

[84] Aalborg Industries website – www.aalborg-industries.com

[85] Iver Ivesen – "Nitrogen Inert Gas Systems Based on Membrane Technology" – Unitor ASA – 1999

[86] "Defence Standard 02-102 (NES 102) – Requirements for Air Conditioning & Ventilation" – Issue 2 – UK Ministry of Defence – September 2000

[87] "Rules and Regulations for the Classification of Naval Ships" – Lloyd's Register of Shipping – January 2001

[88] "Fifth Report from the Commission to the Council on the Situation in World Shipbuilding" – COM(2002) 205 – Commission of the European Communities – Brussels – April 2002

[89] D. Fellows – "Surface Ship Economical Analysis" – Excel Spreadsheet – University College London – 2001

[90] Inmarsat website – www.inmarsat.com

[91] Teledesic website – www.teledesic.com

[92] List of Internet Accessible Machines – www-cse.ucsd.edu/users/bsy/iam.html

[93] Peter Chalk – "Piracy Re-Emerges as a Modern-Day Threat" – Jane's Navy International – May 2002

[94] International Maritime Bureau Piracy Reporting Centre website – www.iccwbo.org

[95] "Masters Courses Ship Design Data Book" – Naval Architecture Research Group – University College London – London – 2001

Annex 4 – Reliability Analysis

The following assumptions were made in this analysis:

a) A constant failure rate λ was assumed for each equipment and an exponential reliability time distribution ($R(t)$) was used in the calculations, where:

- $R(t) = e^{-\lambda t}$, where
- $\lambda = 1/MTTF$

b) The failure of any item was considered to have no effect on the probability of failure of other items, i.e. all events in the system were considered as independent.

c) The overall Mean Time to Failure (MTTF) of series and parallel elements was calculated in accordance to the following formulas:

- $MTTF = \int_0^{\infty} R(t)dt$
- In a series system, $R(t)_{system} = R_1(t) \times R_2(t) = e^{-\lambda_1 t} \times e^{-\lambda_2 t} = e^{-(\lambda_1+\lambda_1)t} \Rightarrow MTTF = \dfrac{1}{\lambda_1+\lambda_2}$
- In a parallel system, $R(t)_{system} = 1 - (1 - e^{-\lambda_1 t}) \times (1 - e^{-\lambda_2 t}) = -$ $e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1+\lambda_1)t} \Rightarrow MTTF = \dfrac{1}{\lambda_1} + \dfrac{1}{\lambda_2} + \dfrac{1}{\lambda_1+\lambda_2}$

Reliability data was estimated for each element of the system, in accordance to references [63], [64], [65] and [66], as seen in the following Table:

Annex 5 – Initial Sizing

As already mentioned in Chapter 6, this is an iterative process and only the final results will be listed in this Annex.

1) Payload Data

(i) Number of containers = 301 TEU

(ii) Number of containers homogeneously loaded to 14 ton = 190

(iii) Number of containers beneath the upper deck ($N_{c(bud)}$) = 72

(iv) $V_{cont(bud)} = 38.5 \times N_{c(bud)} = 2772\ m^3$

(v) Packing efficiency (η_c) = 0.85

(vi) $V_{intCargo} = \dfrac{\mathrm{Vcont(bud)}}{\eta_c} = 3261\ m^3$

(vii) Weight of Cargo (W_c) = 190 x 14 = 2660 ton

2) Initial Estimation of Volume (will only be used in the first iteration)

(i) Payload volume fraction (pvf) = 0.35

(ii) $V = \dfrac{\mathrm{VintCargo}}{\mathrm{pvf}} = 10056\ m^3$

3) Initial Displacement Estimation (will only be used in the first iteration)

(i) Overall density (ρ) = 0.48

(ii) Displacement (Δ) = $\rho \times V$ = 4865 ton

4) Volume of Displacement (∇)

(i) Density of Seawater (ρ_s) = 1.026 ton/m^3

(ii) $\nabla = \dfrac{\Delta}{\rho_S} = 4742\ m^3$

5) Determination of Main Hull Volume

(i) Superstructure proportion (v_s) = 0.37 (see Figure 54 and add forecastle and hatch coamings volume)

(ii) $V_m = V \times (1 - v_s) = 6325\ m^3$

6) Main Hull Displacement Proportion (ρ_m)

(i) $\rho_m = \dfrac{Vm}{\nabla} = 0.75$

7) Immersed Hull Dimensions

(i) B = 15.85m

(ii) D = 6.18m

(iii) $k_B = B/T = 3.25 \Rightarrow T = 4.88m$

(iv) Assume □ = 6.0 (kept constant in all iterations)

(v) Assume C_M = 0.988 (kept constant in all iterations)

(vi) L =□ x $\nabla^{1/3}$ = 100.80m

(vii) $C_B = \dfrac{\nabla^{2/3}}{k_B \times T^2 \times M} = 0.609$

8) Powering

(i) Values of surface area and residuary coefficient were calculated from reference [58] and combined with values of C_F and C_A, resulting in P_E = 1389 kW

(ii) Including a margin of 10% for appendages, $P_{EA} = 1.1 \times P_E$ = 1528 kW

(iii) Assuming a propulsive coefficient (PC) of 0.6, $P_{S(Service)} = \frac{P_{EA}}{PC} = 2546$ kW

(iv) Including a margin of 10% as an allowance for bad weather, $P_{S(mcr)} = 1.1 \times P_{S(Service)} = 2801$ kW

9) Propulsive Plant Weight and Volume

(i) Weight of main engine = 40 ton (considering the engine fitted in the Conofeeder 300 series)

(ii) Weight of remainder = $0.69 \times mcr^{0.7} = 179$ ton

(iii) Total Machinery Weight (W_{mcy}) = 219 ton

(iv) Machinery Space Volume (V_{mcy}) = $5.16 \times W_{mcy} = 1131$ m^3

10) Outfit Weight and Volume

(i) $W_{outfit} = 0.33 \times L \times B = 527$ ton (from reference [59])

(ii) $V_{outfit} = 1050 + 80 \times Np = 1850$ m^3 (considering that the Conofeeder 300 has a 10 person complement)

11) General Stores Weight and Volume

(i) Ttrip = 7 days

(ii) $\rho_{GS} = 0.2$ ton/m^3

(iii) $V_{GS} = 140 + 0.1 \times Np \times Ttrip = 147$ m^3

(iv) $W_{GS} = V_{GS} \times \rho_{GS} = 29$ ton

12) Refrigerated Stores Weight and Volume

(i) $V_{RS} = 0.04 \times Np \times Ttrip = 2.8$ m^3

(ii) $\rho_{RS} = 0.1$ ton/m^3

(iii) $W_{RS} = V_{RS} \times \rho_{RS} = 0.3$ ton

13) Fresh Water Weight and Volume

(i) $V_{FW} = 9 \times Np = 90\ m^3$

(ii) $W_{FW} = 90$ ton

14) Fuel Weight and Volume

(i) As already explained, the volume of fuel will be equal to the capacity of the Conofeeder 300 – 273 m^3

15) Hull Structure Weight and Volume

(i) Since the aim is to derive a hullform as similar as possible to the Conofeeder 300, the same structural arrangement with a 1.27 m double bottom and a side skin of 1.325 m will be used. Those spaces will be used to accommodate the fuel and ballast tanks.

(ii) $E = L \times (B + T) + 0.85 \times L \times (D - T) + 200 = 2400$

(iii) $W_{struct} = 0.033 \times E^{1.36} \times [1 + 0.5 \times (1.05 \times C_B - 0.71)] = 1240$ ton

(iv) V_{struct} = Vol. inside double bottom and side skin = 2226 m^3

16) Margins

(i) $W_{margin} = 0.02 \times (W_{struct} + W_{outfit} + W_{mcy}) = 40$ ton

(ii) $V_{margin} = 0.075 \times V = 754\ m^3$

17) Total Displacement and Volume

(i) $W = \Delta = 4865$ ton

(ii) $V_{req} = 9357\ m^3$

(iii) $V = 10056\ m^3$

Annex 6 – Parametric Survey

The following calculations were performed for a number of different hull form parameters and only the results obtained for the selected ship will be listed in this Annex.

1) Estimation of KG

1.1) Lightship KG

(i) Steelwork $\Rightarrow KG_{steel} = (0.725 - 0.0007218 \times L) \times D = 4.08$ m

(ii) Machinery $\Rightarrow KG_{mcy} = 0.470 \times D = 2.90$ m

(iii) $W_{tot} = W_{crew\ items} + W_{other\ outfit\ items}]$, where $W_{crew\ items}$ was determined through the procedure detailed in Annex 3

(iv) Outfit $\Rightarrow KG_{rest} = [[(1.005 - 0.000689 \times L) \times D] \times W_{tot} - W_{crew\ items} \times KG_{crew\ items}]/\ W_{other\ outfit\ items} = 2.38$ m

1.2) Cargo KG

From the arrangement of containers, assuming that 72 TEU will be transported in the holds and that an extra 10 TEU homogeneously loaded to 14 ton will be transported above the main deck, when comparing to the Conofeeder 300, $KG_{cargo} = 7.93$ m

1.3) Fuel KG

(i) $KG_{fuel} = 0.67 \times h_{DB} = 0.85$ m

So, KG(deep) = 6.24 m

2) Initial Intact Stability

In the Parametric Survey, intact stability will be considered only in terms of GM and the achievement of a satisfactory stability range will be safeguarded by the need to meet a minimum freeboard criterion.

Annex 9 – Running Costs – Benchmark

Full Mechanical Propulsion

Hull type	Unmanned Ship
Maximum design speed	15 knots
Number of shafts	1
Operating profile	Unmanned Ship
Mission duration	219000 hrs (25 years)
Average Service Load	0.49 MW
Fuel unit cost	83 £/tonne

Propulsion Operation	Medium Speed Diesel
Generator Operation	MGO
Electrical Service Load	Average load

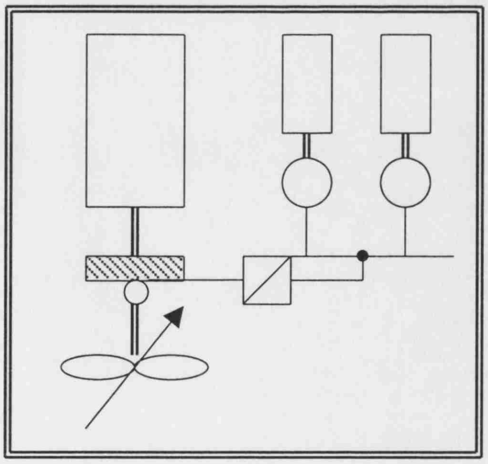
Max achievable speed	15 knots
Most Economic Speed	7 knots
and Fuel Consumption	33.2 miles/tonne
Distance sailed	1180410 miles

Propulsive power at design spd	2.85 MW
Shaft power at design speed	2.91 MW
Available propulsive power	2.98 MW

FUEL USAGE	tonnes
Propulsion engines	39274
Generator engines	23729
TOTAL FUEL	63003

RUNNING COSTS	£k
Propulsion Fuel	3260
Propulsion Maintenance	3592
Generators Fuel	1969
Generators Maintenance	8760
TOTAL RUNNING COST	17581

RUNNING HOURS		Power (MW)	Running Hours
Propulsion Engines			
B1	Generic 3 - 5 MW DG	2.98	89790
Total Running Hours			89790
Generator Engines			
G1	Generic 1 - 2 MW DG	0.25	219000
G2	Generic 1 - 2 MW DG	0.25	219000
Total Running Hours			438000



Annex 10 – Running Costs – IFEP with 2 Advanced Cycle Gas Turbines

Full Electric Propulsion

Hull type	Unmanned Ship
Maximum design speed	15 knots
Number of shafts	1
Operating profile	Unmanned Ship
Mission duration	219000 hrs (25 years)
Electrical Service Load	0.49 MW
Fuel unit cost	120 £/tonne

Engine Operation	Single Engine Minimum Power

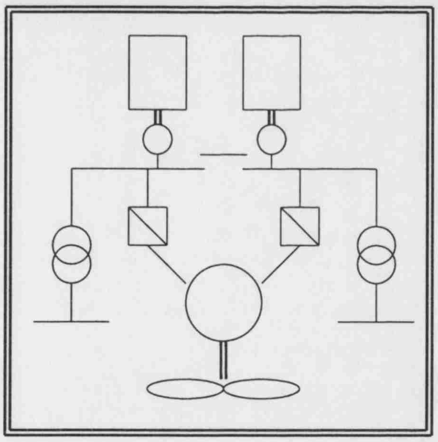
Max achievable speed	15 knots
Most Economic Speed	7 knots
and Fuel Consumption	30.4 miles/tonne
Distance sailed	1180410 miles

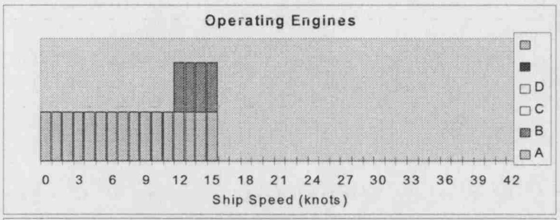
Propulsive power at design spd	2.85 MW
Shaft power at design speed	2.90 MW
Available motor power	3 MW

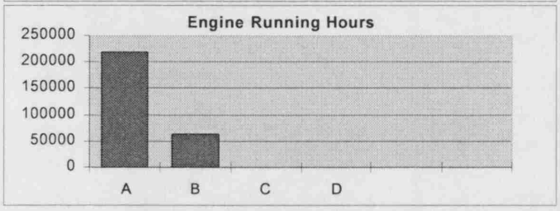
FUEL USAGE (tonnes)	76438

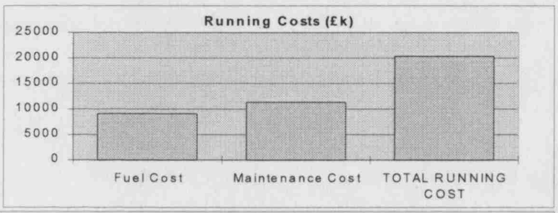
RUNNING COSTS	**£k**
Fuel Cost	9173
Maintenance Cost	11300
TOTAL RUNNING COST	20473

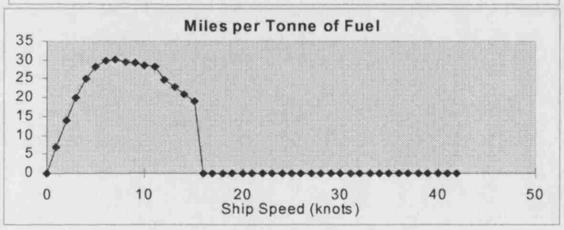
RUNNING HOURS	**Power (MW)**	**Running Hours**
A Generic AdvC GTA - 1.8 MW	1.8	219000
B Generic AdvC GTA - 1.8 MW	1.8	63510
Total Running Hours		282510
Electric Motor (2 per shaft)	1.5	











Annex 11 – Running Costs – IFEP with 2 Simple Cycle Gas Turbines

Full Electric Propulsion

Hull type	Unmanned Ship
Maximum design speed	15 knots
Number of shafts	1
Operating profile	Unmanned Ship
Mission duration	219000 hrs
Electrical Service Load	0.49 MW
Fuel unit cost	120 £/tonne

Engine Operation	Single Engine Minimum Power

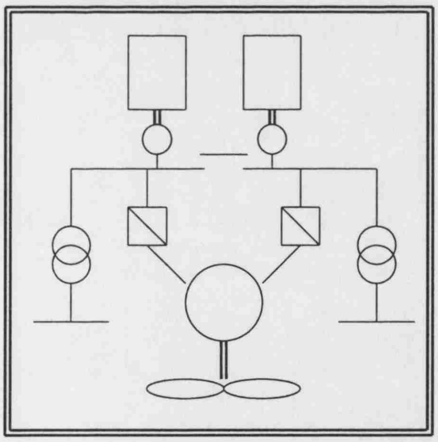
Max achievable speed	15 knots
Most Economic Speed	8 knots
and Fuel Consumption	28.5 miles/tonne
Distance sailed	1180410 miles

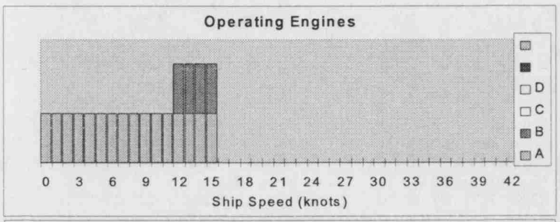
Propulsive power at design spd	2.85 MW
Shaft power at design speed	2.90 MW
Available motor power	3 MW

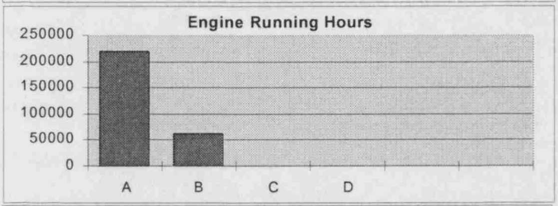
FUEL USAGE (tonnes)	82414

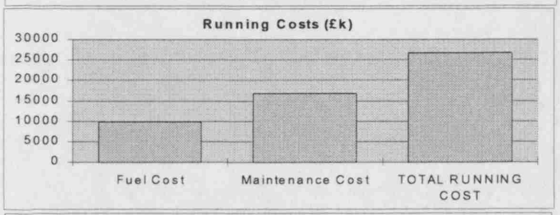
RUNNING COSTS	£k
Fuel Cost	9890
Maintenance Cost	16951
TOTAL RUNNING COST	26840

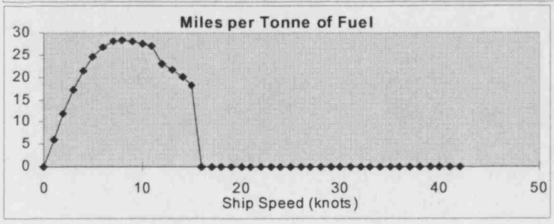
RUNNING HOURS	Power (MW)	Running Hours
A Generic 1.8 MW GT	1.8	219000
B Generic 1.8 MW GT	1.8	63510
Total Running Hours		282510
Electric Motor (2 per shaft)	1.5	











Annex 12 – Running Costs – IFEP with 4 Diesel Generators

Full Electric Propulsion

Hull type	Unmanned Ship
Maximum design speed	15 knots
Number of shafts	1
Operating profile	Unmanned Ship
Mission duration	219000 hrs (25 years)
Electrical Service Load	0.49 MW
Fuel unit cost	83 £/tonne

Engine Operation	Single Engine Minimum Power

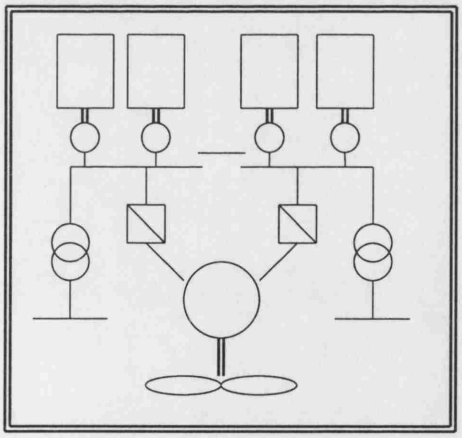
Max achievable speed	15 knots
Most Economic Speed	6 knots
and Fuel Consumption	35.3 miles/tonne
Distance sailed	1180410 miles

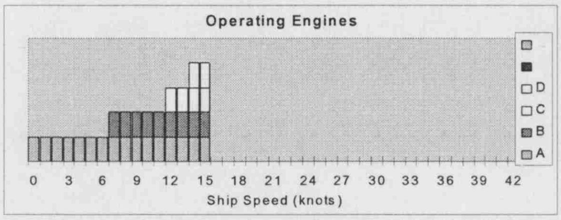
Propulsive power at design spd	2.85 MW
Shaft power at design speed	2.90 MW
Available motor power	3 MW

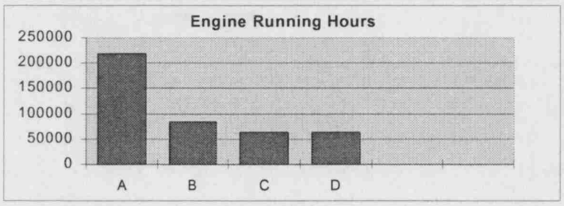
FUEL USAGE (tonnes)	69432

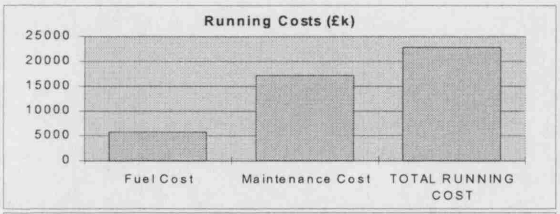
RUNNING COSTS	£k
Fuel Cost	5763
Maintenance Cost	17257
TOTAL RUNNING COST	23020

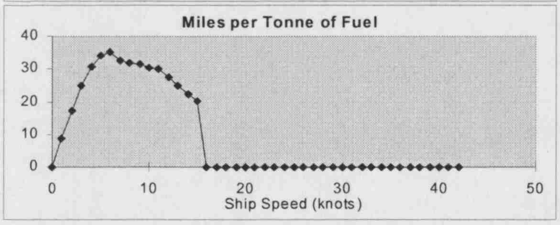
RUNNING HOURS	Power (MW)	Running Hours
A Generic 1 - 2 MW DG	0.9	219000
B Generic 1 - 2 MW DG	0.9	85410
C Generic 1 - 2 MW DG	0.9	63510
D Generic 1 - 2 MW DG	0.9	63510
Total Running Hours		431430
Electric Motor (2 per shaft)	1.5	











Annex 13 – Running Costs – Mechanical with 4 Diesel Engines

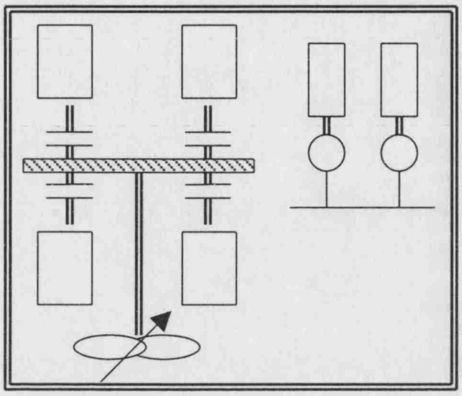
Full Mechanical Propulsion

Hull type	Unmanned Ship
Maximum design speed	15 knots
Number of shafts	2
Operating profile	Unmanned Ship
Mission duration	219000 hrs (25 years)
Average Service Load	0.49 MW
Fuel unit cost	120 £/tonne

Propulsion Operation	CODAD
Generator Operation	MGO
Electrical Service Load	Average load

Max achievable speed	15 knots
Most Economic Speed	6 knots
and Fuel Consumption	32.5 miles/tonne
Distance sailed	1180410 miles

Propulsive power at design spd	2.85 MW
Shaft power at design speed	2.91 MW
Available propulsive power	2.92 MW



FUEL USAGE	tonnes
Propulsion engines	45824
Generator engines	23729
TOTAL FUEL	69553

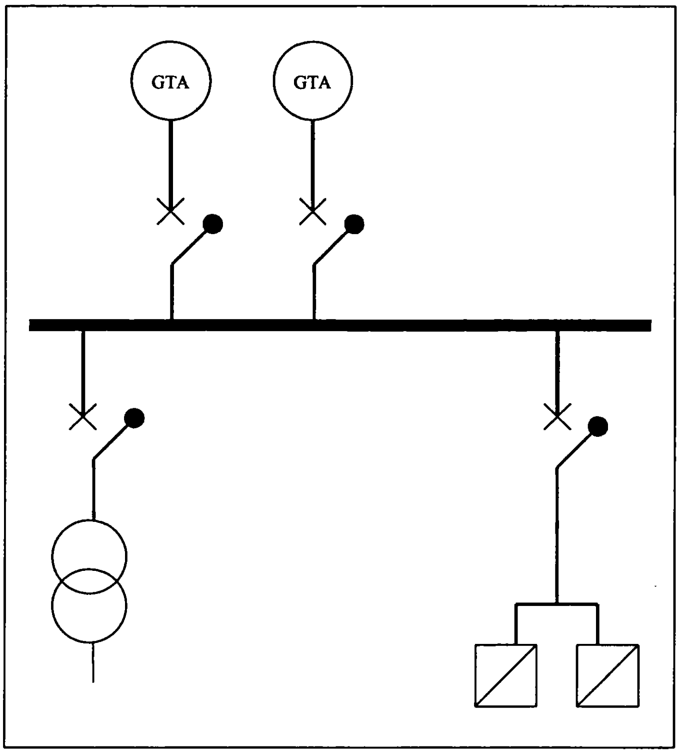
RUNNING COSTS	£k
Propulsion Fuel	5499
Propulsion Maintenance	9067
Generators Fuel	2847
Generators Maintenance	13140
TOTAL RUNNING COST	30553

RUNNING HOURS	Power (MW)	Running Hours
Propulsion Engines		
C1 Generic 1 - 2 MW DG	0.73	89790
C2 Generic 1 - 2 MW DG	0.73	85410
B1 Generic 1 - 2 MW DG	0.73	63510
B2 Generic 1 - 2 MW DG	0.73	63510
Total Running Hours		302220
Trailing shaft factor	1.14	
Generator Engines		
G1 Generic 1 - 2 MW DG	0.25	219000
G2 Generic 1 - 2 MW DG	0.25	219000
G3 Generic 1 - 2 MW DG	0.25	0
Total Running Hours		438000

Annex 14 – Fault Current Calculations

In order to perform the calculations in accordance with Reference [77], the following assumptions were made:

- Subtransient reactance (Xd") = 0.14 pu for the generators;
- Power factor = 0.9
- Power regeneration from the propulsion motor was not considered;
- Cabling reactances were neglected;
- Worst-case scenario assumed as two GTA in parallel at full power.



Generators rating = 2.0 MVA

MVAbase = 2.0 MVA

Equivalent impedance Xeq = $\dfrac{1}{1/0.14 + 1/0.14} = 0.07\,\text{pu}$

Fault Level = $\frac{\text{MVAbase}}{\text{Xeq}} = \frac{2.0}{0.07} = 28.6 \text{ MVA}$

The short circuit rms symmetrical current for this system is given by:

I = $\frac{\text{Fault Level}}{\sqrt{3} \times \text{V}}$

Calculating for different voltages:

	440 V	690 V	3.3 kV
I (kA)	37.5	23.9	5.0

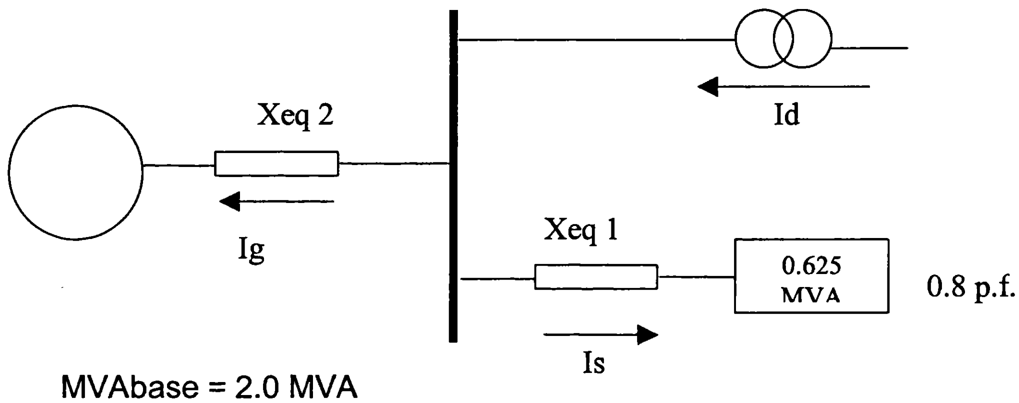
The maximum capacity of circuit breakers available today is around 50 kA [78], which could lead to the choice of a 440V busbar, both for propulsion and for hotel load.

According to the ACS 600 MarineDrive W characteristics, however, the equipment operates at 690V, which resulted in the selection of that voltage for the propulsion busbar.

Annex 15 – Harmonic Distortion Calculation

The following assumptions were made:

1) Subtransient reactance (Xd") = 0.14 pu for the generators;
2) Transformer reactance considered as 4.5% @ 0.625 MVA.
3) Cabling reactances were neglected;
4) Since a diode front end is used in the DTC drive, harmonic currents were considered as $I_n = I_f / n$, where I_n = n^{th} harmonic current and I_f = fundamental current;



MVAbase = 2.0 MVA

Vbase = 0.69 kV

$$\text{Ibase} = \frac{\text{MVAbase}}{\sqrt{3} \times \text{Vbase}} = 1673 \text{ A}$$

Xeq 1 = 0.144 pu @ 2.0 MVA

Xeq 2 = 0.070 pu @ 2.0 MVA

For the system we have:

Ig + Is = Id

Ig x Xeq 2n = Is x Xeq 1n

$$\text{So, } \text{Isn} = \frac{\text{Id}}{\left(1 + \frac{\text{Xeq1n}}{\text{Xeq2n}}\right)}$$

Where Xeq1n and Xeq2n are the reactance values at the n^{th} harmonic.

The total harmonic distortion can then be calculated as:

$$\text{THD} = \frac{\sqrt{\sum \text{Isn}^2}}{If}$$

Considering up to the 51st harmonic, the value of THD was estimated as 10%, which is more than the limit defined by Classification Societies rules, leading to the need of a harmonic filtering equipment in the system.

Addendum

- Page 19 – Include:

  CPA : Closest Point of Approach

  TCPA : Time to Closest Point of Approach

- Page 28 – 5th paragraph:

  … because of the little general appeal …

- Page 40 – 1st paragraph:

  … constant training became more important than ever.

- Page 54 – 2nd paragraph:

  It was only in the mid-1990's, however, with the widespread use of the Global Positioning System (GPS), that most marine users have started to migrate from Radiobeacon direction finding, Loran-C and Transit to satellite navigation as their primary electronic navigational aid (See Figure 14).

- Page 55 – last bullet point should be deleted

- Page 56 – 3rd bullet point:

  Tropospheric delays caused by changes in temperature, …

- Page 57 – 2nd paragraph:

  … on October 13th, 2000 after having been postponed several times [17].

- Page 67 – 2nd paragraph:

  Figure 20 and Figure 21[34] indicate …

- Page 67 – 3rd paragraph:

  … as shown in Figure 22 and Figure 23 [25].

- Page 73 – 1st paragraph:

  … and the other highly dependent on ground base components.

- Page 74 – 5th paragraph:

  Since this solution …

- Page 89 – Table 8:

Phase	Required Accuracy	Available Accuracy	Required Fix Interval	Available Fix Interval
Ocean				
Coastal		1m – 0.25nm		
Harbour Approach				

- Page 120 – Last paragraph:

  … as can be seen in Figure 41 …

- Page 141 – 2nd paragraph:

  … due to radio frequency radiation can form the basis of the unmanned ship communication system.

- Page 154 – 2nd paragraph:

  Since the benchmark ship hull form parameters were not available, it was decided …

- Page 180 – 2nd paragraph:

  The main differences between both designs are (see also Annex 22):

- Page 210 – Annex 3

	Area	Volume	Weight	Cost
Other Officers			1.2	£33,113
…				…
Total Cost				£1,364,308

- New Annex 22 – Unmanned Ship x Conofeeder 300:

	Conofeeder 300	Unmanned Ship
L (m)	92.48	92.48
B (m)	15.85	15.85
D (m)	6.18	6.18
Lightship Displacement	1060 ton	754 ton
TEU Capacity(max)	301	321
Propulsion	Medium speed diesel engine driving a controllable pitch propeller through a gearbox	Integrated Electric Propulsion with two advanced cycle gas turbines and a pod